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: Output and Results

Table of Contents

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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 a summary of the post-workshop findings, followed by the full reports generated by the DRM teams and the teams' summary reports.

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Summary: Post-Workshop Findings

SMD analyzed workshop discussions and the post-workshop findings of the Design Reference Mission (DRM) teams and determined that several key autonomous capabilities are needed to enable the functions required by the future mission scenarios considered at the workshop:

Autonomous Capability	Required Functions
Robust and efficient long duration/long distance operations	Fault detection, correction, and recovery; monitoring/evaluating health, activities, and resources; situation- and self-awareness; making decisions and acting accordingly
In situ data analysis, modeling, and prioritization	Sample analysis, big data analysis, machine learning, developing and refining models, prioritizing data and acting accordingly
GNC	terrain-relative navigation, auto trajectory corrections, proximity operations, targeting
Mobility	moving on, below, and/or above the surface of a body—often in extreme conditions
Perception	detecting and responding to an event; calibration; multi-resolution data fusion
Multi-agent task planning and coordination/collaboration	Planning and coordinating movement, actions, and measurements of multiple, heterogeneous assets
Manipulation	Collection and handling of science samples or assembly of components in space
In-space assembly	Assembly of complex from multiple components

In addition, other supporting technologies must be developed/advanced to support infusion of the autonomy that will enable the DRM scenarios considered:

- Advanced computing and storage, including onboard and big data capabilities, machine learning
- Communication: DTN and low-mass, low-power, high bandwidth communications capabilities
- Propulsion, especially for small satellites
- Physical and virtual testbeds
- Lightweight, radiation-hardened instruments/sensors (optics, LiDAR, etc.)
- Modeling capabilities
- Algorithm development

Furthermore, SMD identified several important technical takeaways from the workshop discussions and post-workshop activities:

Autonomy is both function-specific and cross-domain: The autonomy technology that is required depends on the mission destination, the mission architecture, the concept of operations, types of platforms used, the risk profile, etc. These aspects influence how autonomous functions are implemented and integrated into the system or "system of systems."

Common themes and recurring functional needs emerged from workshop DRM activities: The autonomous capabilities and functions in the table above are key to achievement of the DRM scenarios, and could indicate areas where additional resources could effectively be applied.

Autonomous data interpretation and modeling capabilities are uniquely challenging in the space environment: For example, the autonomous machine learning capabilities required to support the DRM scenarios considered require extensive training data and models that are currently not available for the respective destinations in space. Existing terrestrial models and data are not necessarily representative of desired space targets. Comprehensive, physics-based, learned models (low-volume, in situ trained) need to be developed, as do associated high-performance spacecraft computing capabilities. Furthermore, using and interpreting data from different assets and missions requires calibration/co-registration of the various sensors.

Advanced autonomy requires advanced software, firmware, and hardware: For example, the RAD750 processor has been employed at the Agency for ~30-years and cannot handle the autonomy needs of future missions. Different and improved sensors are also needed to enable autonomous situation/self-awareness capabilities required to support the DRM scenarios analyzed. Furthermore, the unique environmental conditions in which space-based missions operate (e.g., very high temperature, high radiation, etc.) and space missions’ low size, weight, and power requirements often differ from those of commercial terrestrial-based autonomous applications. Therefore, many assumptions inherent to such commercial autonomous systems and algorithms may not extend to space-based applications; these technologies must be further advanced to enable space-based missions.

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The Astrophysics Design Reference Mission Report

Part I: Abstract

Astrophysics Overview

As we persevere in our quest to answer the fundamental questions of science by peering into the heart of the universe, we strive for ever larger apertures to see better than what we can see today. In a domain of science where every photon counts, the size of the aperture is directly correlated to better science. But past experiences have shown that developing a large observatory to fit, even when folded, into a single launch fairing of an existing or a future planned launch vehicle has various technological, programmatic, schedule, and cost challenges. Is there a way to mitigate these challenges for future observatories and improve the cost and risk postures of their implementations? Further, servicing these observatories in space to extend their lifetimes and update instruments for many decades of scientific returns is also a challenging aspect. How will future observatories have the same opportunity of being serviced? To address these issues, NASA and other government entities are expressing growing interest in exploring the value proposition of in-space robotic assembly and servicing for large space assets including optical telescopes. This interest is also reciprocated by industry through internal investments and public-private partnerships.

Design Reference Mission

We study the autonomous in-space robotic assembly and servicing of a 20-m, filled-aperture, segmented, ultraviolet/visible/near-infrared, non-cryogenic observatory from its modular components in cislunar orbit. The mission is to use multiple launches for the modules. The observatory is to have instruments updated at its operational environment i.e., SE-L2. Mission components include the observatory spacecraft, robotic systems for assembly and servicing, and cargo delivery vehicles (that bring the modules to the assemblage) that will work together to assemble the observatory. We explore how autonomy can enable this DRM scenario.

Critical Autonomy Capabilities

We find that the success of this DRM is predicated on the successful development of both system-level and functional-level autonomy. Functional-level autonomy corresponds to the robotic behaviors associated with the detailed assembly steps while the system-level autonomy orchestrates these functional-level steps by monitoring, tracking, and reasoning over a large state-space of the overall system and environmental effects. Among different autonomy features, we focused on the following key autonomous aspects:

- Autonomous Onboard System Manager.
- Autonomous Maneuvers, Mobility and Manipulation.
- Autonomous In-space Verification/Validation.
- Autonomous Onboard Anomaly Detection.

A few representative key autonomy technologies needed for this DRM scenario are:

- Dexterous, precise manipulation, manipulation of soft goods, manipulation with minimal induced stresses
- Sensing and perception for contact-based, precision assembly
- Anomaly detection and fault response

- Distributed actuation, sensing, and control
- Multi-agent coordination, planning, and control

Findings

The Astrophysics DRM team finds that the following actions and activities would facilitate implementation of the mission scenario described above:

- Consider funding a technology-gap analysis and technology roadmap activity with emphasis on identifying autonomy capabilities that may be leveraged from other space or terrestrial applications.
- Consider setting up virtual and physical test beds in laboratory settings for technology development and risk reduction demonstrations with equal emphasis on system- and functional-level autonomy.
- Consider in-space demonstrations or risk-reduction efforts using small spacecraft or existing assets (e.g., inside and outside the International Space Station [ISS]).

Part II: The Case for In-Space Assembly of Large Observatories

In-space assembly has emerged as a timely and credible approach over the last decade. How well it can be mapped to assembly of an observatory remains a challenge[1,2]. Following are some key features to consider that relate to in-space assembly of large observatories.

- With key capabilities demonstrated in space over the last decade, in-space assembly (ISA) has emerged as a viable approach for observatory assembly. Engineering development needs and technology gaps for specific observatory designs will have to be addressed.
- ISA removes the constraint of fitting the entire observatory in a single, specific launch vehicle by enabling use of multiple launches. This enables observatory and instrument designs that better suit the science goals and not the mass and volume constraints of fitting in a single fairing.
- The ISA approach is scalable and can enable observatory sizes that cannot be achieved by conventional, single-launch approaches. The largest filled-aperture telescope deployed from a future 8-10m fairing appears to be about 15m in size. Anything larger will likely need ISA.
- ISA offers an in situ approach to servicing the observatory and replacing instruments by reusing the onboard robotics needed to assemble the observatory in space. Conventional, single-launch approaches need an external additional servicer to be developed. ISA does not need additional servicing infrastructure.
- ISA changes the risk posture of observatory development and makes it potentially more manageable.

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[1] Mukherjee, R., et al. "The Case for In-Space Assembly of Telescopes to Advance Exoplanet Science." https://exoplanets.nasa.gov/internal_resources/839/. Accessed 16 January 2020.

[2] Mukherjee, R., et al. "When is it Worth Assembling Observatories in Space?" https://exoplanets.nasa.gov/internal_resources/1254/. Accessed 16 January 2020.

- ISA may offer opportunities for reducing the costs of conventional, single-launch observatories particularly when including the servicing infrastructure in the mission. This will depend ultimately on the point design selected and its technology needs.

Current State of Art: Concepts for in-space assembly have been discussed for a long time, including a concept for assembly of the James Webb Space Telescope (JWST). Hence, it is natural to ask, what developments have occurred over the last decade to make ISA relevant now? Since the last Decadal Survey, some of the key enabling capabilities of ISA have technologically matured by being demonstrated and used in space. The ISA paradigm is built on the following key capabilities: (i) modularity, (ii) multiple launches, (iii) rendezvous and proximity operation (RPO), (iv) Cargo Delivery Vehicles (CDVs), (v) robotic assembly, and (vi) in-space verification and validation (V&V). The current state-of-art in these components is summarized in Table 1.

#	ISA Key Capabilities	Status	Representative Examples	Readiness for Observatory ISA
1	Modular Elements	Flight Demonstrated	Instruments on HST, instruments installed on ISS	Low
		Active Development	JWST primary mirror segments	
2	Launch Vehicles	Flight Demonstrated	SpaceX Falcon, Falcon Heavy, ULA's Delta IV	High
		Active Development	SLS, Blue Origin, Starship, Vulcan Centaur	
3	RPO	Flight Demonstrated	DARPA Orbital Express, NASA OSIRIS-Rex, Cygnus, Dragon, Crew Dragon, ATV, HTV, Progress, Soyuz	High
4	CDVs	Flight Demonstrated	SpaceX Dragon, Cygnus from Northrop Grumman	High
5a	Space Robotics Hardware	Flight Demonstrated	Several robotic arms on ISS (e.g. Canadarm 2), Orbital Express robotic arm, Mars Rover arms, Shuttle arm	High
		Active Development	NASA Restore-L and DARPA RSGS robotic servicing arms, Canadarm 3, Maxar's Dragonfly arm, Mars 2020 rover	
5b	Space Robotics Software	Flight Demonstrated	Mars Rover Autonomy (e.g. MSL, MER), ISS, Orbital Express	Medium
		Active Development	Mars 2020, Mars Sample Return, NASA Restore-L, DARPA RSGS, NASA Tipping Point Demonstrations	
6	In-space Verification and Validation	Flight Demonstrated	Instruments on HST, instruments installed on ISS	Low
		Active Development	JWST primary mirror segments and wavefront control	

Table 1: Component capabilities needed for ISA are described here. However, technologies specific to assembling an observatory need to be studied in detail. (Reproduced from the white paper summarizing the results of the In-Space Assembled Telescope [iSAT] Study[3].)

The last decade has also seen the successful infusion of robotic instrument installation on the ISS into NASA's Science Mission Directorate portfolio of science missions, particularly in Earth Science. The Orbiting Carbon Observatory 3 (OCO-3) and the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) are the latest examples. The Study ISA concept has a lot of commonality with this approach of instrument installation, including the use of CDVs, RPO, use of robotic arms, installation of modular instruments using a standard interface, and in-space verification and validation of the robotic installation.

NASA identified ISA as being at a "Tipping Point" of wide commercial infusion and made significant investments towards the public-private-partnership-based In Space Robotic Manufacturing and Assembly

[3] Mukherjee, R., et al. "When is it Worth Assembling Observatories in Space?" https://exoplanets.nasa.gov/internal_resources/1254/. Accessed 16 January 2020.

program (IRMA). The IRMA program is slated to have in-space demonstration(s) of robotic assembly in the next few years. NASA and the Defense Advanced Research Projects Agency (DARPA) have invested heavily in space missions for robotic servicing scheduled for launch in the early to mid-2020s. Furthermore, the National Space Strategy 2018 has asked NASA to lead the exploration of capabilities for in-space assembly, servicing and manufacturing. Unlike past decades, the technology maturation and programmatic pull makes ISA relevant now.

One of the key missing capabilities is autonomy. While assembly via astronauts or high bandwidth, human-in-the-loop telerobotics has been demonstrated in the past, this DRM scenario is predicated on the use of autonomous robotic assembly because of the following concerns, among others.

- The time delay due to orbit location (Sun-Earth–L2 and Earth-Moon–L2)
- The large state-space of variables that has to be tracked and reasoned over during assembly
- The deliberate contact-based assembly and in situ verification and validation needed
- The dimensions and inertias of the modules
- The multiple concurrent blind mates that are needed for assembly
- The sensitivity to disturbances and contamination of the assemblage
- The overall mission cost and risk posture

Part III: The Design Reference Mission

DRM Scenario: In-space Assembly of Large Observatories

NASA SMD has chartered a study, the In-Space Assembled Telescope (iSAT) study, to explore the value proposition of in-space assembly of future telescopes. Among other steps, this ongoing study has:

- engaged a large community of practitioners,
- developed a reference telescope architecture,
- designed a reference telescope in terms of modular components for in-space assembly,
- evaluated different orbits for assembly and operations,
- explored different robotic systems for assembly, and
- developed a reference concept of operations.

This study leverages experience from past (e.g., Hubble Space Telescope [HST]) and ongoing astrophysics missions (e.g., JWST) as well as robotics missions (e.g., ISS, Mars robotics, Restore-L, Robotic Servicing of Geosynchronous Satellites [RSGS]) among others. It evaluated the opportunities in cost and risk postures for in-space assembled telescopes of sizes 5m, 10m, 15m and 20m. This DRM leverages the findings of the SMD ISAT study to explore the opportunities presented by autonomy in facilitating the DRM scenario.

The Concept of Operations:
A detailed concept of operations for the assembly of the iSAT reference observatory can be found in the iSAT ConOps Storyboard[4] and the major steps are graphically shown in Figure 1 below. These steps are similar to the instrument assembly approach used on the ISS (e.g., OCO-3).

[4] Mukherjee, R., et al. "iSAT ConOps Graphical Storyboard:

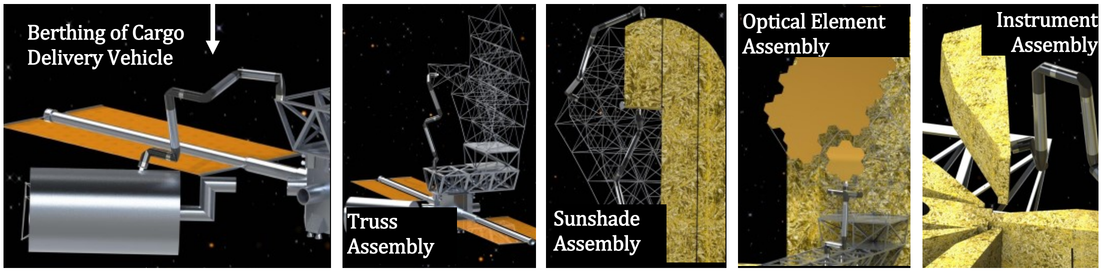

Fig 1. Artistic rendition of representative robotic assembly steps for the Study's iSAT reference concept.

Modularized Design of the Observatory: The observatory is designed as an assembly of separate modules with standardized interfaces. The modules are individually developed, tested on the ground, and launched from one or more launch vehicles. They are designed as precision structures with thermal control to meet stability requirements. These modules are equipped with grapples and interfaces for robotic manipulation, assembly, and adjustability to meet desired accuracy requirements. They may also provide communication, power, and fluid connections. Some module interfaces may also be reversible for servicing.

Launch and Cargo Delivery: The first launch carries the observatory spacecraft, two robotic arms, and first set of modules. The spacecraft forms the foundation of the assemblage. In doing so, it removes the programmatic dependence on any additional platforms such as the International Space Station (ISS) or a potential NASA Gateway. Subsequent launches may have rendezvous and proximity operation (RPO)-capable Cargo Delivery Vehicles (CDVs) or "smart upper stages" to deliver the modules to the assemblage. Alternately, it is also possible to have a dedicated space tug (e.g., Mission Extension Vehicle).

Robotic Manipulation and Assembly: The robotic arms onboard the assemblage berth the CDV to the observatory spacecraft and then unload and relocate individual modules to their assembly locations. Similar to the robots on the ISS, the assembly robots may be designed to be capable of mobility across the assemblage using its end effectors and pre-designed grapple points. Using standard interfaces, supervised autonomy (similar to Mars rovers or better), vision-guided localization, and force-controlled dexterous manipulation, the robots assemble the individual modules to the assemblage. The assembly steps are validated in space (e.g., using metrology or telemetry from the modules themselves) with minor adjustments made by the robots to meet assembly specifications. Engineers on the ground may supervise these steps.

Servicing: This process of launching modules, delivery to the assemblage, and robotic assembly continues in iterative steps until the observatory is fully assembled. The arms remain with the observatory after assembly is completed. If subsequent servicing is needed, a new module is delivered using the same approach as used for assembly and the onboard robot arms conduct the servicing. No additional servicing infrastructure is needed.

In summary, the major technical differences from conventional, single-launch approaches are: (1) modularity, (2) multiple launches, (3) RPO, (4) CDVs, (5) robotic assembly, (6) in-space verification and validation (V&V) and adjustments, and (7) built-in servicer.

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20 m Segmented UV/V/NIR Telescope." https://exoplanets.nasa.gov/internal_resources/1171/. Accessed 16 January 2020.

We envision the need for different autonomous behaviors, examples of which include, but are not limited to:

- rendezvous and berthing,
- manipulation of the modules in unloading from the fairing,
- mobility over the assemblage to reach different assembly locations,
- force-controlled, vision-based, dexterous manipulation for assembling the modules,
- manipulation of soft goods in assembling a large sunshade from modular elements,
- attitude control of the combined assemblage (spacecraft and stack) during assembly,
- metrology-guided adjustments to the assembly,
- inspection of the modules and subassemblies,
- servicing via refueling or instrument replacement, and
- the overall verification and validation of the assembly.

While a detailed technology gap analysis and road mapping activity for in-space assembly of observatories has not been conducted, and we suggest such an activity be funded as the next step, following are some key technology challenges specific to observatory assembly.

- assembly of modules to form precise, linear, thermally stable trusses,
- multi-agent collaboration and autonomous assembly,
- manipulators walking on trusses while reducing induced stresses,
- manipulation of soft goods for to sunshade assembly,
- attitude control with moving center of mass during assembly, and
- precise joining interfaces for robotic assembly and servicing.

Autonomy Capabilities Needed

During the Autonomy Workshop breakout sessions, the DRM team discussed the autonomy technology needs, status or readiness of the technologies, and the criticality of the technology and used this information to identify three key thematic areas of capability need. Within each thematic area, the team listed different component autonomy technologies. This activity was informed by the Autonomous Systems Taxonomy developed by the NASA Autonomous Systems Capability Leadership Team. The results are discussed below, and the reader is encouraged to be mindful that new autonomy needs may emerge as this DRM scenario is studied in more granularity through the iSAT study or future efforts.

Autonomous technologies needed for this capability:	**Other supporting technologies needed**	**Related/relevant R&D projects**	**Potential challenges/risks and key points/questions**
• Anomaly Detection • Fault Response • Sensing and Perception • State Estimation and Monitoring • Knowledge and Model Building • Motion Planning • Dexterous, Precision Manipulation • Gossamer Structure Manipulation • Soft Goods Manipulation • Force-Torque Control • Situational and Self Awareness • Algorithms in sensor fusion • Distributed actuation • Sensing and control • Planning/Execution • Hierarchical tasknet • Tasknet V&V • Framework for system-level autonomy interfaces	• Systems Engineering for autonomy, i.e., what are requirements specific to autonomy, how is it architected, implemented, verified and validated? • Robotics-informed “joining” hardware • End Effectors for robots • Perception Sensors • Computing for vision processing • Modeling and Simulation • Anomaly Detection (enhancing) • Framework-compliant controllers and SW • Non-Destructive Evaluation (NDE) approaches • Metrology • Active Optics • Modular deployable components, particularly soft goods	• NASA Restore-L • DARPA RSGS • Experimental Satellite System-11 (XSS-11) (RPO) • Tipping Point (IRMA) • Mars Robotics Missions • ISS robotics • Ground based telescope assembly • DoD and commercial activities in multi-agent systems • Autonomous boats • Deep Space-1 • Earth Observing-1 • Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) Technology Development	• Can robots autonomously assemble stiff, thermally stable, structures from modules? • Can the system manage the large state-space of variables and facilitate the different functional autonomy level steps needed while managing resources and monitoring environmental factors? • Can the autonomous robotic systems detect and recover from anomalies without causing catastrophic damage to the system? • Can a synergistic autonomy architecture be implemented that is inherently scalable in terms of the number of variables it manages or tracks, as well as be hierarchical, i.e., range from system-level down to detailed functional-level autonomy? • What is the right balance of virtual, in-laboratory, and in-space testing and demonstration needed to assure autonomy?

1. Autonomous Onboard System Manager.

In-space assembly and servicing will require planning for coordination between many different agents (e.g., spacecraft, robots, delivery vehicles), management of resources and environmental effects, and ensuring system-level performance by sequencing and monitoring many different functional-level autonomous behaviors. This is an enabling feature.

This is an **Enabling** capability: "Integrate capabilities with the flight system." There are multiple factors that drive the necessity of an onboard "spacecraft manager" in order to support in-space assembly. This spacecraft manager is a Planner/Executive software for spacecraft routines and a set of interface requirements to ensure that the spacecraft manager has sufficient information to control the different aspects of the spacecraft.

First, spacecraft are currently operated using command sequences, where each command is associated with an execution time. For an autonomous spacecraft, sequences are too brittle to be feasible, as operational anomalies, like a robotic action taking a longer period of time, or failures, like a missed grasping operation, will mean that the commands the spacecraft is executing do not correspond to the actual circumstances the sequence or command was designed for. System-level autonomy uses task networks, or tasknets, to operate a spacecraft. This is a different paradigm where each command is associated with a set of states that are required for successful execution. For instance, a task for attaching a reflector will only be executed once the position state requirement of the reflector is actually met.

The second factor driving the necessity of system-level autonomy is resource management. Spacecraft are complex, with commands being executed by different subsystems that all utilize the same resources like energy, time, attitude, etc. Currently, resource management is handled by spacecraft mission planners who develop command sequences. However, if there are delays associated with anomalies or failures, then it is possible that commands would begin to use resources in an unpredictable way and endanger the mission. For instance, an anomaly in ISA results can cause delay, leading to excess power use during eclipse and energy depletion. In contrast, system-level autonomy would command robotic controllers in small task steps, like individual manipulations, each time requesting resource requirements from the controller. It would then schedule these ISA tasks in a manner that does not disrupt spacecraft health and safety.

Third is the requirement of graceful spacecraft safing that results in function preservation. This is met by using tasknets and resource management in conjunction with onboard anomaly detection. Contingency tasknets can be designed that respond to detected anomaly states, which are then scheduled or immediately executed. Moreover, these contingency tasknets can respond to operational anomalies. In the case of a slow reflector panel assembly that may take longer to execute than a single orbit, the Executive software may schedule the contingent action to safely stow the robotic arm until the spacecraft is out of eclipse by first requesting a safe stow point from the robotics controller.

2. Autonomous Maneuvers, Mobility and Manipulation.

The complement of the system-level manager is the many different functional-level autonomous behaviors needed to assemble and service the observatory. Robotic systems have to autonomously "Go where needed" and "Manipulate what is needed." Autonomous orbital maneuvers for spacecraft berthing and attitude control, autonomous robotic mobility over the assemblage to access different locations, and autonomous manipulation (including soft goods) in assembling different types of modules of the observatory are key enabling features. These contact-based behaviors have to be successfully executed subject to a large state-space of variables that need to be monitored, tracked, or controlled.

This is an **Enabling** capability. Autonomous orbital maneuvers for spacecraft berthing and attitude control, autonomous robotic mobility over the assemblage to access different locations, and autonomous manipulation in assembling different types of modules of the telescope are key enabling features of this DRM.

Autonomous orbital maneuvers for far-field rendezvous, near-field rendezvous, and terminal capture for berthing are a needed capability for supplying the assemblage with different modules. These modules may be delivered to the assembly site from different types of launch systems ranging from propulsive Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) rings to Cygnus-type systems. These systems may have varying levels of rendezvous and proximity operations (RPO) capabilities with different levels of control authority and sensing. Autonomy capabilities will be needed for RPO and berthing of these supply vehicles to the telescope assemblage. Along with safe operations, autonomous capabilities will be needed to minimize the disturbances from these behaviors. Similarly, autonomy capabilities will be needed for attitude control of the assemblage, as well as the stack arising from the berthing of the supply vehicle to the assemblage. This may be a distributed actuation problem requiring a kind of multi-agent collaboration between the telescope spacecraft and the supply vehicle. Autonomously controlling the stack attitude also becomes important due to the changing center of mass (*cm*) as the robot repositions modules (or itself) along the assemblage.

The DRM has baselined long-reach "walking" robotic manipulators. These are manipulators are much like the Canadarm on the ISS. It is expected that the robots for this DRM would be able to carry modules from the fairing to their assembly location by "inch-worming" over the assemblage by grappling the assemblage at specially designed interfaces. These grappling behaviors would involve perception-guided force-controlled manipulations with different types of contact loads.

The manipulators would have to access the supply fairing to access the delivery module. The manipulators would then have to safely carry the payload to its assembly location. The manipulator also must attain a configuration where it can have the freedom of workspace and dexterity to assemble the modules. During the mobility of the manipulator by itself, or the manipulator while carrying a payload, the overall *cm* of the assemblage may move, thereby impacting the attitude control. Thus, autonomous coordination between the manipulators and the spacecraft will be required during mobility. Manipulator mobility may also be required in areas with potential obstacles, e.g., truss work under assembly. This may arise when moving a payload. A manipulator has to autonomously plan for the mobility of not only itself, but the different payload modules it may be carrying.

The manipulators would also have to autonomously manipulate all the payloads during the different phases of assembly including rigid elements as well as soft goods such as sun-shade elements. The manipulators may have to enable several concurrent contacts and force-controlled assembly of the payloads. These assembly interfaces may be hard-hard (e.g., truss to truss), soft-hard (e.g., sunshade elements to truss) and even soft-soft (e.g., stray-light-blocking soft goods). Multi-sensor-informed, autonomous, dexterous manipulation of these force-controlled interactions between payloads with different interfaces is a key enabler. The manipulator should autonomously handle a variety of materials, such gossamer structures, as well as soft goods uncertainties arising from environmental factors (e.g., lighting conditions) and properties intrinsic to the manipulator or payload (e.g., thermal drift, manufacturing tolerances). These manipulations have to be precise to meet the tolerances allocated from the optical requirement of the telescope. The manipulators may also have to reach crowded workspaces to adjust the assemblage to achieve the desired tolerances. The manipulators may have to conduct a variety of perception-guided, force-controlled "joining" behaviors, some of which may be actuated while others may be passive.

3. Autonomous In-space Verification/Validation

Autonomy is needed to "Check your work." An observatory assembly has strict requirements for precision of module placement, structural stability, operational thermal control, among many others. In addition to the precise assembly, the validation of assembly should be continual and enabled by incorporating different kinds of sensors and autonomous behaviors.

This is an **Enabling** capability. A telescope assembly has strict requirements for precision of element placement, structural rigidity, operational material temperature, and resonant characteristics. In addition to the precise assembly of structural and optical elements already mentioned, the validation of construction should be continuous and enabled by incorporating non-traditional sensors on the assembling robot. These sensor payloads can largely be borrowed from the field of Non-Destructive Evaluation (e.g., laser-excited ultrasonics, thermography, model-based photogrammetry, etc.), but require novel sensor fusion techniques to be incorporated into anomaly detection and manipulation planning.

In-space V&V can be separated into two categories, Operational and Diagnostic. Operational V&V allows the assembling agent to better detect anomalies during assembly steps by providing sensory feedback used during manipulation planning or control. Diagnostic V&V allows the agent to act as a servicing agent during fault recovery or during the long lifetime of the telescope—either autonomously or by leveraging human-commanded diagnostic behaviors (e.g., "Take *this* measurement of *these* joints").

Ground V&V campaigns will need to be conducted of all assembly modules and the assembly agent itself. As an additional requirement, the results of these V&V campaigns will likely need to be used by the assembly agent to completely characterize the acceptable range of sensor readings, thus enabling the kind of assured anomaly detection that is required for large-scale telescope assembly in space.

4. Autonomous Onboard Anomaly Detection.

This scenario involves deliberate contact between autonomous agents and modules, some of which may have fragile components. It is critical that the system be robustly autonomous to ensure that the contact-based events perform within the bounds of nominal behaviors via continuous and autonomous anomaly detection. Furthermore, it is paramount that the system autonomously and gracefully transitions from different anomalous situations to safe states (i.e., safing) where engineers on the ground can intervene to recover. While autonomous recovery would be an ultimate goal, autonomous detection and graceful safing is a key requirement.

This is an **Enabling** capability: "Do no harm." This DRM comprises of many different kinds of behaviors demonstrated by the spacecraft, the robotic system, and multi-agent interactions—i.e., between spacecraft, robot, and resupply vehicle. Many of these interactions involve deliberate contact with fragile components (e.g., reflectors) during assembly and adjustments. These interactions would be significantly dependent on different types of sensors, their calibrations, fusion of multiple sensors and impact of the environment on the sensors (e.g., lighting conditions, thermal drift). These interactions would also involve control of different types of actuators (e.g., robot joint actuators, thrusters, ACS systems), coordination between these actuators, and environmental impact on these actuators. This is a many-element problem involving diverse types of elements (multi-system, individual system, coordination of sensors and actuators, down to individual sensors and actuators) that all have to work together to achieve nominal behaviors. As the interactions between all these hierarchical elements involve repeated and deliberate contact, any off-nominal scenario or anomaly can be catastrophic to the assemblage. Furthermore, as the assembly may involve non-reversible joints, damage to the assembly from an anomalous contact may be unrecoverable. Hence, it becomes paramount that the system be robustly autonomous in ensuring that it is performing within the bounds of nominal behaviors via continuous and autonomous anomaly detection. While autonomous recovery would be an ultimate goal, <u>autonomous detection and graceful safing is a key requirement.</u>

Two levels of anomaly detection and safing could be implemented based on the granularity of the autonomous behaviors. The first is short-term autonomy mode, e.g., a single, element-level behavior after which assembly robots await human responses or commands. During this phase, the system would autonomously detect an anomaly, safe itself gracefully, inform ground systems, and wait for recovery instructions. Example: the system should be able to assemble two modules together through vision-based localization and force control. It should be able to detect off-nominal forces, loss in calibration, inadequate lighting, or visibility, among other factors. And the system should autonomously stop its behavior at a juncture where it is safe to do so. Abrupt stopping may actually be more harmful.

The second type of anomaly detection and safing concerns long-term autonomy. Here the system is expected to carry out a number of different behaviors autonomously that are mutually dependent or involve more discrete planning. For example, consider an aggregate behavior where the robot is tasked to autonomously deploy a structural module and then assemble it to the assemblage with one instruction from the ground system. During this phase, the system would be responsible for autonomously detecting variations in the scene and adapt its behaviors accordingly. It would also be able to autonomously detect an impending "system-level" anomaly even if the element-level behaviors are nominal, while still providing the same responsiveness to anomalies of individual element-level behaviors. An example of this type would be autonomous capabilities that sense and aggregate dimensional tolerances of components to determine that the next component will not fit. In this case, the robot would go back and adjust the assembly before assembling the next module.

Element-level behaviors (the first type above) are enabling. System-level behaviors (the second type) are enhancing. An autonomous system without the first type of anomaly recovery is impractical for this DRM. The second type, when appropriately verified and validated, would significantly reduce the overall cost and risk posture of an ISA DRM.

Part IV: Findings

The Astrophysics DRM team finds that the following actions and activities would facilitate implementation of the mission scenario described above:

- Consider funding a technology-gap analysis and technology roadmap activity with emphasis on identifying autonomy capabilities that may be leveraged from other space or terrestrial applications.
- Consider setting up virtual and physical test beds in laboratory settings for technology development and risk reduction demonstrations with equal emphasis on system- and functional-level autonomy.
- Consider in-space demonstrations or risk-reduction efforts using small spacecraft or existing assets (e.g., inside and outside the ISS).

NASA is already investing in the area of in-space assembly and servicing through, for example, the Restore-L project and the In Space Robotic Manufacturing and Assembly program (IRMA). However, these programs are unlikely to embrace the full capabilities of autonomous robotic assembly due to their deployment in Low Earth Orbit and the availability of a short time delay. Hence, this DRM team suggests that specific technologies for autonomous assembly be explored further and matured through test beds and demonstrations.

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The material presented in this document has been based primarily on the findings of the iSAT study (that was conducted by the team identified below) with additional inputs from the DRM team.

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The Earth Design Reference Mission Report

Part I: Abstract

Few Earth-observing satellites in operation today have instruments that can be used to stare at a specific Earthside location. Almost all of these are manually commanded, using several days of instrument command formulation and testing, followed by transmission to the platform mission operations center, followed by more testing and eventual upload to the satellite with further testing and confirmation.

Recently, the Earth Science community has experimented with ballistic constellations of satellites—small spacecraft and their associated instruments—with autonomous control of instruments and aircraft flights. This has revealed new opportunities for studying physical phenomena and natural processes that previously were not accessible from space. It also allows a more direct coupling with models, including the possibility of directing observations to update models, based on assessment of the quality of model output. The Earth Design

Reference Mission (DRM) team proposes the following DRM scenario in which autonomy can be incorporated to enable and enhance innovative Earth-observing systems.

Model-Driven Observing Strategy.

This is an observing strategy for Earth science driven by models. As the model needs more data, it provides direction to the observing system to collect specific data from certain regions and of specific conditions (i.e., sea-surface temperature in the Sea of Japan) and report it back by the fastest possible route. The resulting model forecasts are then evaluated to verify the needed improvements.

Autonomy would be enabling for this DRM for workflow management, model quality assessment, satellite control, and tasking prioritization and deconfliction, among other capabilities.

Critical Autonomous Technologies

The critical autonomous technologies that will enable this scenario are **situation and self-awareness, reasoning and acting, collaboration and interaction**, and **engineering and integrity**, including:

- *Sensing and perception*
- *State estimation and monitoring*
- *Event and trend identification*
- *Anomaly detection*
- *Behavior and intent prediction*
- *Verification and validation*

These technologies will enable the following capabilities:

- Selection of the appropriate asset
- Resolving conflicts and issuing the necessary tasking without human intervention
- Monitoring workflow, detecting and compensating for faults
- Verifying completion of the improved forecast

Supporting technologies that are needed for this scenario include:

- Onboard processing
- Adaptive computer security (multi-mission, threat response)
- Models capable of continuous operations and identifying regional degradations
- Assimilation models supporting irregular input
- Collision avoidance as collaboration with other assets (i.e., non-NASA)
- Autonomous mission evaluation; including testing, safety evaluation, threat detection.

Findings

The Earth DRM team finds that the following actions and activities would facilitate implementation of the DRM scenario described above. The next step would be to establish and debug a ground-based testbed upon which to develop and evaluate the integration capabilities needed to make this functionality available to the Earth-science community. This experimental environment would be used to evaluate the current state of the various components. It would also be used to evaluate alternative observing strategies and to assess the relative complexity of each. Other next steps include:

- Developing computational forecast models of physical processes and natural phenomena that run in a more real-time and continuous way.
- Further developing the airborne mission-management software to be used with models, in situ and on-orbit components, as well as airborne assets.
- Developing a mission-operations concept in which the role of humans is to oversee and potentially override the autonomous system. This involves a significant human-factors analysis and evaluation, possibly similar to what is being done in NASA's Aeronautics Research Mission Directorate (ARMD) or the Human Exploration and Operations Mission Directorate (HEOMD).
- Developing a fairly comprehensive autonomous Model-based Safety Analysis capability so that all autonomous and manual decisions are evaluated as they are being formulated for safety (and collision avoidance) implications.

Part II: The Case for Earth

Recently, the emergence of small spacecraft as science-quality observing platforms has created a new set of opportunities, as noted by the National Academy of Sciences in the 2017 Decadal Survey. First, some of the traditional observing strategies can be performed with less expensive platforms so more instruments can be placed in orbit to perform global-mapping missions with higher revisit rates, when appropriate. Second, the use of constellations of satellites permits study of transient or transitional natural phenomena or natural processes that could not have been observed from space before. Third, multiple spacecraft can be used to improve measurement quality and signal-to-noise ratios when used as an array, flying in formation all aimed at the same location.

Flying strings of satellites permits longer duration observations of the same location than afforded by single satellites with long-revisit rates. Flying an array of satellites permits the observing of a phenomenon simultaneously from different angles, either with the same or different instruments. Flying a configuration of satellites with the same instruments can also be used to form a phased array which can improve spatial resolution, or accuracy. Today, such constellations fly in a pattern because they are injected into certain orbits on ballistic trajectories with limited manual orbit adjustments. Few satellites today have instruments that can be used to stare at a specific Earthside location; almost all of these are manually commanded, using several days of instrument command formulation and testing, followed by transmission to the platform mission operations center, followed by more testing and eventual upload to the satellite with further testing and confirmation. Both types of these largely manual adjustments have considerable latency built in.

The emergence of small spacecraft has also generated a rapidly growing commercial remote sensing industry due to the reduced cost of acquiring, launching and maintaining an operational observing system. This means that instrument output is available for a price from devices not owned by the Federal Government. Furthermore, this commercial market has also created a new industry in commercial ground station services, such as those by Swedish Space Corporation, Konigsburg Space and Amazon Web Services, thereby reducing the latency in downlinking observational data due to ground station location and availability.

These new observing strategies are useful in a variety of missions to support both research and operational capabilities. New research can be accomplished leading to a more-complete understanding of transient and transitional natural phenomena and physical processes where the time constants involved required multiple observations in close proximity and others where the necessary revisit rate is on the order of hours. Table 1 describes the science domain and new studies that are enabled this way.

Domain	Physical Processes	Revisit Rates
Biodiversity	● Green wave ● Diurnal vegetation activity ● Carbon transfer	Ideally, hourly. At least every 3 hours during daylight
Cryosphere	● Sea ice formation/melt ● Ice flows ● Changes in water flow under glaciers ● Seasonal changes in soil	Daily
Water Cycle	● Surface water ● Snow accumulation/melt ● Soil moisture ● Flooding (modeling and disaster response)	Daily
Air Quality	● Planetary boundary layer	2-3 times daily or less

	changes	

Table 1: Sample of Earth Science Domains and Observations Enabled by the New Observing Strategy (Note: Revisit rates require validation)

The Earth-science community has experimented with ballistic constellations of satellites, with small spacecraft and their associated instruments, and with autonomous control of instruments and aircraft flights. This work has revealed some opportunities for studying natural phenomena and physical processes that previously were not accessible from space. These mission scenarios also allow a more-direct coupling with models, including the possibility of directing observations to update models, based on assessment of the quality of model output.

This concept supports both research and operational models. In the case of research, the investigator seeks to improve the representation of the scientific knowledge of the relevant phenomenon; by manipulating an appropriately designed model, it could be used to drive the observing regime needed to collect relevant data to study specific phenomena. In the case of operational forecasting, the operator seeks to improve the skill level of the model by setting a minimum threshold at which the system would recognize the need for improving skill level, task the observing system to acquire the observations needed, recompute the forecast, and validate the improvements as the ones needed.

Another onboard function could be to prioritize data to be transmitted, e.g., when an anomaly is detected.

Part III: Design Reference Mission

DRM Scenario: A Model-Driven Observing Strategy

This DRM describes an observing strategy for Earth science driven by models. As the model needs more data, it provides direction to the observing system to collect specific data from certain regions and of specific conditions (i.e., sea-surface temperature in the Sea of Japan) and report it back by the fastest possible route. The resulting model forecasts are then evaluated to verify the needed improvements.

This approach is useful in both research and operations, depending on what the model is trying to do. In the case of research, it might be to improve deficiencies in the understanding of physical processes, as reflected in the model. In the case of operations, it might be to maintain a minimum level of quality in the forecast skill level.

The Concept of Operations

Currently, models of natural processes are run in a batch strategy, either on demand or on a recurring schedule. Observational data is assimilated in batches and then fed into the initialization of the model run. Future models are envisioned to run on a continuous basis, feeding in new data as it becomes available. Such models are expected to be used in areas such as weather, surface hydrology, snow, precipitation, oceanography, atmospheric composition and surface biology and geology.

For operational forecasting, as the model runs and identifies diminishing forecast-quality in a location/region, it identifies observational data that is needed to restore quality. An autonomous supervisory system then determines the most effective strategy for collecting the needed data, tasks the observation elements (satellite, airborne, ground or in situ) to collect and report data. The data are then assimilated and the model components updated, and the quality re-assessed to ensure the expected improvements have occurred.

For research into a process or phenomenon, this approach would run a repeating test/debug cycle on models to improve their ability to predict the behavior of the physical processes and natural phenomena. A researcher would assess the efficacy of the model and then define an experiment or a campaign to collect data, do analysis, adjust the model and repeat the process, making incremental improvements to more accurately understand and represent specific parts of a process or phenomenon.

Control of the observing assets will be handled through a supervisory program that runs collects and analyzes data about both the environment and the observing system. The autonomous operations are supervised by human operators that adjust high-level priorities and monitor an internal diagnostic system that executes contingencies and directs maintenance and repair actions when needed. Computer security threats are similarly detected and mitigated by the supervisory system, alerting operators to emerging abnormal operations and keeping them apprised of the issues as they emerge.

Assumptions

- Models have dependable mechanisms for assessing quality of forecasts (e.g., skill level) and can identify observations at the sub-global scale needed to improve quality;
- Models of physical processes and natural phenomena of interest are developed in such a way to leverage updated non-global observational data at the regional level rather than requiring new global input to have any impact.

Autonomy is needed for this DRM for the following purposes:

- Workflow management, including assessing the quality, determining the optimum resource to use to collect the needed data at the time it is needed.
- Model quality assessment throughout the model run.
- Control of the satellites, mission adjudication and prioritization, and deconfliction of tasking.
- Maintain system operations for an indefinite period of time, including system calibration, executing contingency plans, and maintenance and repair actions.
- An effective presentation of just the right amount of information to keep the human aware of the state of the system under varying conditions. Some characteristics that might require operator intervention include the quality of the forecast, resource

consumption, etc. This will require an entirely new approach to console presentation to ensure humans play an appropriate role.

The Autonomy Capabilities needed:

Selection of the appropriate asset. When a model indicates it needs data, there may be several choices of instruments and platforms to provide that data; they may be constrained by the quality and availability of the set of instruments. Autonomy would be needed to select and task the measurement capability. The accuracy and the characteristics of the measurement ability of each instrument (or class of instruments) affects its ability to satisfy the needs of the model to bootstrap itself into a higher-quality forecast. Adequate observations may come from multiple instruments on different platforms from different vantage points. This complex optimization requires autonomy to be accomplished in time and to create and check the observing instrument/platform tasking.

Resolving conflicts and issuing the necessary tasking without human intervention. Time scales for tasking are at the second and minute level and are likely to be substantially different each time they are needed. Human operators are unable to respond as quickly and with low enough error to manually perform the optimization and subsequent tasking.

Monitoring workflow, detecting and compensating for faults. For an autonomous, model-driven observing system to operate it must monitor the health of the system—at both the component level and the system level—so that it can task functional components. In a complex interconnected system, with many different demands and many pathways and thousands of failure modes, continuous monitoring and decision making will be necessary to identify faults and to reroute around them. Keeping humans informed and aware without delaying fault repair will be critical. Human operators will become quality assurance and adjusters of the system, which means they need a console and controls that enable high-level supervision, not micromanagement.

Verifying completion of the improved forecast. Forecasts are complex representations of a non-linear, inhomogeneous, dynamic natural system. Improvements to either research or operational models expected as the result of observing system tasking must be validated to ensure the resulting forecast actually supplied the improvements expected and, if not, additional observations and or processing may be required. The autonomous observing system must assess these improvements, alert the operators and direct additional corrective action. Analysis of the resulting quality, after the forecast has been started and at various stages, will be necessary—as well as an appropriate level of information about success to be presented to the human supervisor.

The Autonomous technologies needed for all of these capabilities:

- Algorithms for use in autonomy
- Retasking
- Optimization of multiple heterogeneous assets
- Dynamic recalibration on-orbit
- Intelligent data understanding
- Low-load algorithms for detecting desired observations
- Model self-assessment and identification of corrective action

Achieving these autonomous technology capabilities will require advancements in all of the elements listed in the Autonomous Systems Taxonomy (AST) document developed by NASA's Autonomous Systems Capability Leadership Team.

Other non-autonomous technologies needed to support these capabilities:

- Onboard processing
- Adaptive computer security (multi-mission, threat response)
- Models capable of continuous operations and identifying regional degradations
- Assimilation models supporting irregular input
- Collision avoidance as collaboration with other assets (i.e., non-NASA)
- Autonomous mission evaluation; including testing, safety evaluation, threat detection
- Human-machine interface when the human oversees a system instead of operating it

The Relevant Research and Development Projects for this DRM

- Advanced Information Systems Technology (AIST) Competed Projects (2005-2022)
- Intercalibration Theory Study (NASA Earth and Space Science Fellowship) (2019)
- AIST Blockchain Study (2018)
- Trade-space Analysis Tool for Constellations (TAT-C) (GSFC) (ongoing)
- Multi-platform mission planning and operations (Ohio State University) (ongoing)
- Amazon Web Services (AWS) Groundstation as a Service Experiment (JPL) (2019)
- Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) processing and opportunistic data communications experiments (JPL) (2019-2020)
- AIST New Observing Strategy (NOS) ground test bed (2019-2020)
- Defense Advanced Research Projects Agency (DARPA) Blackjack (ongoing)
- United States Geological Survey (USGS) Innovation Center Software Defined Radar (SDR) (ongoing) for soil moisture
- Starling/Shiver Project (NASA Ames Research Center, U.S. Air Force)

The Potential Challenges, Risks, or Questions for this DRM

Most of the technologies needed for this type of observing strategy have been developed and demonstrated for other purposes. However, the integration has not. The new autonomy is primarily needed to integrate the components into a working, cohesive, large-scale system. This model-based observing strategy represents a major shift in the design of certain missions, including those that observe transient and transitional phenomenon and events. This effort would require a progressive demonstration of the capabilities and eventually a demonstration of the science value of the observing strategies that are dependent upon the autonomy. Full implementation would be degradable to a manually operated mission with substantial reduction in science data, but building this degradation into the mission is not a common practice in NASA. This is a radically more-complex observing system than we use today, but offers substantial improvements to the types of phenomena/processes we can study. The sociology of the science community represents a substantial risk, in its skepticism of new technologies and the ability to conceptualize what the potential is, what risks need to be retired, and how to experiment with the technology to retire risks. Demonstrations of these capabilities are needed to show the value to the science community.

To be truly effective, this type of observing strategy requires collaboration among a wide range of separate and independent entities. Most of the components have been or will be developed by different organizations and establishing the collaboration will be another difficult problem.

Current models of natural phenomena and physical processes are batch-oriented, computationally intensive, and slow. Both production forecast models and research models assume the availability of batch-loaded assimilation data for initialization. Estimates of skill level are at a gross level and need to be regionalized to determine where, when, and how degradation of forecasts is occurring.

Autonomous flight-control software has been developed at the Defense Advanced Research Projects Agency and other Department of Defense facilities. This software does not interact with widespread distributed assets of wide variation and needs to be further developed to expand into in situ and on-orbit platforms, as well as airborne assets. It also needs to be integrated with human operators in an appropriate oversight/override role.

Part IV: Findings

For the Earth Science Program, selecting an appropriate set of research and applied science domains upon which to try experiments is necessary. To date, teams studying the Energy and Water Cycle (specifically, hydrology), Air Quality, and the Cryosphere have indicated needs for model-driven observing capabilities. Since much of the autonomy is in the integration of emerging, but relatively mature, components, the use of a ground-based testbed would be a useful way to demonstrate the value of a model-driven observing system and to debug the integration of the individual components. When a working and conceptually useful system can be demonstrated, the next step would be to fly one of the sensing nodes on orbit and demonstrate that the system as a whole would be useful and feasible. Then a full observing system could be developed with appropriate flight-mission components. The Earth DRM team finds that the following actions and activities would facilitate implementation of the DRM scenario described above.

- Develop a ground-based, multi-site, multi-party testbed to mature the technology integration and to enable development of technologies that can be integrated.
- Run experiments for each of the science communities needing persuasion of the value of this type of observing strategy and the ability of the autonomous operations to provide more and better data than the conventional approach.
- Develop a theoretical basis for intercalibration among instruments to enable integrated and near real-time data consumption as input into the control system.
- Develop computational forecast models of physical processes and natural phenomena that run in a more real-time and continuous way.
- Further develop the airborne mission-management software to be used with models, in situ, and on-orbit components, as well as airborne assets.
- Develop a mission operations concept in which the role of humans is to oversee and potentially override the autonomous system. This involves a heavy human-factors analysis and evaluation, possibly similar to what is being done in NASA's Aeronautics Research Mission Directorate (ARMD) or the Human Exploration and Operations Mission Directorate (HEOMD).
- Develop a fairly comprehensive autonomous model-based safety analysis capability so that all autonomous and manual decisions are evaluated as they are being formulated for safety (and collision) implications.
- Develop an effective model-based computer security capability for protecting assets from rapidly evolving cybersecurity threats and for monitoring and assessing the state of NASA-owned assets as well as those of other collaborators.

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Part VI: References

Alderson, D. L. and J. C. Doyle, "Contrasting Views of Complexity and Their Implications for Network-centric Infrastructures, *IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans*, vol. 40, no. 4, 2010.

Arnold Jr., C. P. and C. H. Dey, "Observing-systems simulation experiments: Past, present, and future," Bull. Am. Meteorol. Soc., vol. 67, no. 6, pp. 687–695, 1986.

Christian, J. A., "A Quantitative Approach to Assessing System Evolvability," 2004.

de Weck, O., R. De Neufville, and M. Chaize, "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit," *J. Aerosp. Comput. Information, Commun.*, vol. 1, no. March, pp. 119–136, 2004.

de Weck, O. L., U. Scialom, and A. Siddiqi, "Optimal reconfiguration of satellite constellations with the auction algorithm," *Acta Astronaut.*, 2008.[Ros04] A.M. Ross, D. E. Hastings, J. M. Warmkessel, and N. P. Diller, "Multi-Attribute Trade-space Exploration as Front End for Effective Space System Design," *Journal of Spacecraft and Rockets*, 41(1):20-28, 2004.

Feldman, D. R., C. A. Algieri, J. R. Ong, and W. D. Collins, "CLARREO shortwave observing system simulation experiments of the twenty-first century: Simulator design and implementation," *J. Geophys. Res. Atmospheres 1984–2012*, vol. 116, no. D10, 2011.

Foreman, V., J. Le Moigne and O. de Weck, "A Survey of Cost Estimating Methodologies for Distributed Spacecraft Missions," *American Institute of Aeronautics and Astronautics (AIAA) SPACE 2016*, Long Beach, CA, September 13- 16, 2016.

Grogan, P. T., O. L. de Weck, A.M. Ross, and D. H. Rhodes, "Interactive Models as a System Design Tool: Applications to System Project Management," *Procedia Computer Science* 44:285-294, 2015 Conference on Systems Engineering Research, 2015.

Hitomi, N. and D. Selva, "A Classification and Comparison of Credit Assignment Strategies in Multiobjective Adaptive Operator Selection," *IEEE Transactions on Evolutionary Computation*. 2016. Accepted.

Hitomi, N. and D. Selva, "A hyper-heuristic approach to leveraging domain knowledge in multi-objective evolutionary algorithms," in *Proceedings of the ASME 2016 International Design*

Engineering Technical Conferences & Computers and Information in Engineering Conference DETC/CIE 2016.

Hitomi, N. H. Bang, and D. Selva, "Extracting and Applying Knowledge with Adaptive Knowledge-driven Optimization to Architect and Earth Observing Satellite System," in *AIAA nfotech@Aerospace Conference*, 2017.

Le Moigne, J., P. Dabney, O. de Weck, V. Foreman, P. Grogan, M. Holland, S. Hughes, and S. Nag, "Tradespace Analysis Tool for Designing Constellations (TAT- C)," *2017 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'17,* Fort Worth, TX, July 23-28, 2017.

Le Moigne, J., J.C. Adams, P. Dabney, M. Johnson, D. Leisawitz, F. Lemoine, S. Nag, W. Powell, D. Smith, K. Thome, S. Tompkins, and W. Wiscombe, 2017, "An Overview of Distributed Spacecraft Missions (DSM)," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS)*, in preparation.

Nag, S., C. K. Gatebe, and O. de Weck. "Observing System Simulations for Small Satellite Formations Estimating Bidirectional Reflectance." *International Journal of Applied Earth Observation and Geoinformation* 43 (2015): 102–18.

Nag, S., C. K. Gatebe, T.Hilker, "Simulation of Multiangular Remote Sensing Products Using Small Satellite Formations," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 99, June 2016.

Nag, S., S. Hughes, and J. Le Moigne, "Streamlining the Design Tradespace for Earth Imaging Constellations," *American Institute of Aeronautics and Astronautics (AIAA) SPACE 2016*, Long Beach, CA, September 13-16, 2016.

NASA Climate Change/Vital Signs of the Planet, "NASA Small Satellites Will Take a Fresh Look at Earth," http://climate.nasa.gov/news/2512/nasa-small-satellites-will- take-a-fresh-look-at-earth/, November 7, 2016.

Paek, S. W., *Reconfigurable satellite constellations for geo-spatially adaptive Earth observation missions*, PhD Dissertation, Massachusetts Institute of Technology, 2012.

Scott, C. J. and D. B. Spencer, "Optimal Reconfiguration of Satellites in Formation," *J. Spacecr. Rockets*, vol. 44, no. 1, pp. 230–239, 2007.

Siddiqi, A., J. Mellein, and O. L. de Weck, "Optimal Reconfigurations for Increasing Capacity of Communication Satellite Constellations," in *AIAA Space 2005*, 2005, pp.

Silver, M. R. and O. L. de Weck, "Time-Expanded Decision Network: A New Framework for Designing Evolvable Complex Systems," in *AIAA 2006-6964*, no. September, pp. 1–15, 2006.

Turmon, M. J., G. L. Block, R. O. Green, H. Hua, J. C. Jacob, H. R. Sobel, P. L. Springer, and Q. Zhang, "Observing System Simulation Experiment (OSSE) for the HyspIRI Spectrometer Mission," *NASA Tech Briefs*, 34, September 2010.

Wertz, J. R., *Orbit & Constellation Design & Management*, Second Printing, ed. El Segundo. California: Microcosm Press, 2009.

Crow, W., S. Chan, D. Entekhabi, P. R. Houser, A. Y. Hsu, T. J. Jackson, E. G. Njoku, P. E. O'Neill, J. C. Shi, X. Zhan, "An observing system simulation experiment for HYDROS radiometer-only soil moisture products," IEEE Trans. Geosc. Rem. Sens., vol. 43, pp. 1289-1303, 2005.

O'Brien, A., S. Gleason, J. T. Johnson, and C. Ruf, "The CYGNSS End-to-End Simulator," *GNSS+R 2015 workshop*, Potsdam, Germany, proceedings, 2015.

Hoffman, R. N. and R. Atlas, "Future observing system simulation experiments," Bull. Am. Meteorological Soc., pp. 1601-1616, September 2016.

Ruf, C. S., "CYGNSS L2 retrieved wind parameterized error model," version 3, CYGNSS project document, June 24, 2014.

Kim, S. B., L. Tsang, J. T. Johnson, S. Huang, J. J. van Zyl, and E. G. Njoku, "Soil moisture retrieval using time-series radar observations over bare surfaces," IEEE Trans. Geosc. Rem. Sens., vol. 50, pp. 1853- 1863, 2011.

NASA Earth Science Technology Office 2016 Microwave Technologies Review and Strategy, available at: https://esto.nasa.gov/MicrowaveStrategies/index.html

NASA Earth Science Technology Office 2016 Lidar Technologies Review and Strategy, available at: https://esto.nasa.gov/LidarStrategies/index.html

Stephens, G. L., D. G. Vane, S. Tanelli, E. Im, S. Durden, M. Rokey, D. Reinke, P. Partain, G. G. Mace, R. Austin, T. L'Ecuyer, J. Haynes, M. Lebsock, K. Suzuki, D. Waliser, D. Wu, J. Kay, A. Gettelman, Z. Wang, and R. Marchand, "CloudSat mission: performance and early science after the first year of operation," Journal of Geophys. Res. (Atmospheres), vol. 113 (D8), Article D00A18, 2008.

Wu, D. L. et al, "Vertical distributions and relationships of cloud occurrence frequency as observed by MISR, AIRS, MODIS, OMI, Calipso, and CloudSat," Geophys. Res. Let., vol. 36, Article L09821, 2009.

Frankford, M. T., N. Majurec, and J. T. Johnson, "Software-defined radar testbed for MIMO and adaptive waveform applications," IEEE Radar Conference, proceedings, 2010.

Bell, K. L., C. J. Baker, G. E. Smith, J. T. Johnson, and M. Rangaswamy, "Cognitive radar framework for target detection and tracking," IEEE J. Sel. Topics in Signal Proc., vol. 9, pp. 1427-1439, 2015.

Haykin, S., *Cognitive Dynamic Systems: Perception-action Cycle, Radar and Radio*. Cambridge University Press, 2012.

Johnson, J. T., C. C. Chen, A. O'Brien, G. E. Smith, C. McKelvey, M. Andrews, C. Ball, S. Misra, S. Brown, J. Kocz, R. Jarnot, D. Bradley, P. Mohammed, J. Lucey, J. R. Piepmeier, "The CubeSat Radiometer Radio Frequency Interference Technology validation (CubeRRT) mission," IGARSS, proceedings, 2016.

Liu, R. S., P. Sinha, and C. E. Koksal, "Joint energy management and resource allocation in rechargeable sensor networks," INFOCOM, proceedings, 2010.

Chien, S., J. Doubleday, D. Tran, J. Bellardo, C. Francis, E. Baumgarten, A. Williams, E. Yee, D. Fluitt, E. Stanton, and J. Piug-Suari, "Onboard mission planning on the Intelligent Payload Experiment (IPEX) CubeSat Mission," Intl. Workshop on Planning and Scheduling for Space, proceedings, 2013.

Kennedy, A. K., *Resource Optimization Algorithms for an Automated Coordinated CubeSat Constellation*, thesis, Department of Aeronautics and Astronautics, MIT, 2015.

Ruf, C. S., R. Atlas, P. S. Chang, M. P. Clarizia, J. L. Garrison, S. Gleason, S. J. Katzberg, Z. Jelenak, J. T. Johnson, S. J. Majumdar, A. O'Brien, D. J. Posselt, A. J. Ridley, R. J. Rose, and V. U. Zavorotny, "New ocean winds satellite mission to probe hurricanes and tropical convection," Bull. Am. Meteorological Soc., pp. 386-395, March 2016.

Annane, B., B. D. McNoldy, S. M. Leidner, R. N. Hoffman, R. Atlas, and S. J. Majumdar, "Impact of simulated CYGNSS ocean surface winds on tropical cyclone analyses and forecasts in a regional OSSE network," American Meteorological Society Meeting, proceedings, 2017.

Cao, H., E. Ertin, V. Kulathumani, M. Sridharan, and A. Arora, "Differential games in large-scale sensor-actuator networks," Intl Conf. on Information Processing in Sensor Networks, proceedings, 2006.

Moo, P. W., "Scheduling for multifunction radar via two-slope benefit functions," *IET Radar, Sonar Navig.*, vol. 5, no. 8, p. 884, 2011.

Moo, P. W. and Z. Ding, "Adaptive radar scheduling of track updates," *2014 Int. Radar Conf. Radar 2014*, pp. 1–6, 2014.

Blair, W. D., G. A. Watson, T. Kirubarajan, and Y. Bar-Shalom, "Benchmark for radar allocation and tracking in ECM," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 34, no. 4, pp. 1097–1114, 1998.

Nadjiasngar. R. and A. Charlish, "Quality of service resource management for a radar network," in *2015 IEEE Radar Conference*, 2015, pp. 344–349.

Charlish, A., K. Woodbridge, and H. Griffiths, "Phased array radar resource management using continuous double auction," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 51, no. 3, pp. 2212–2224, Jul. 2015.

Ding, Z. and P. W. Moo, "Coordinated radar resource management for networked phased array radars," *IET Radar, Sonar Navig.*, vol. 9, no. 8, pp. 1009–1020, 2015.

Hernandez, M. L., T. Kirubarajan, and Y. Bar-Shalom, "Multisensor resource deployment using posterior Cramér-Rao bounds," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 40, no. 2, pp. 399–416, 2004.

Dhillon, S. S., and K. Chakrabarty, "Sensor placement for effective coverage and surveillance in distributed sensor networks," Wireless Communication and Networking Conference, proceedings, 2003.

Open Message Passing Interface (Open-MPI) project, website https://www.open-mpi.org/ . [29] Interior Point Optimizer project, website https://projects.coin-or.org/Ipopt .

Optimization Software of M. D. Powell, website http://mat.uc.pt/~zhang/software.html#powell_soft- ware .

Constrained and Unconstrained Testing Environment – revisited (CUTEr), website http://www.cuter.rl.ac.uk/ .

Decadal Survey for Earth Science and Applications from Space website, http://sites.nationalacade- mies.org/DEPS/ESAS2017/index.htm .

"Community Input and White Papers" for the *Decadal Survey for Earth Science and Applications from **Space,*** website http://sites.nationalacademies.org/DEPS/esas2017/DEPS_170397 .

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.

The Heliophysics Design Reference Mission Report

Part I: Abstract

Heliophysics Overview

The science of Heliophysics is focused on understanding the formation and evolution of the solar wind and solar ejecta, and how those impact objects in the solar system. In the near future, we expect to send astronauts to the Moon and Mars. As humans leave the safety of Earth's protective magnetic bubble, they will be exposed to the harsh environment of space weather. Safeguarding human and robotic exploration and eventual colonization of the solar system is a prime motivator for this DRM, and autonomous technologies would enable mission success.

Design Reference Mission

The Heliophysics Team suggests two Design Reference Mission (DRM) scenarios that autonomy would enable.

- The **Autonomous Space Weather Constellation** scenario would improve space weather predictions. Its aim would be filling the gaps in our observational capabilities in order to facilitate validated, near-real time, data-driven models of the Sun's global corona, heliosphere and associated space weather effects to safeguard human and robotic exploration throughout the solar system.

- **An Interstellar Probe** scenario would travel to the Local Interstellar Medium (LISM) and measure the environment beyond the solar system. The probe would launch around 2030 and travel 20 AU/year for 50 years to reach 1000 AU. The probe would make comprehensive, state-of-the-art, in situ measurements of plasma and energetic-particle composition, magnetic fields, plasma waves, ionic charge states, energetic neutrals, and dust that are required for understanding the nature of the outer heliosphere and exploring our local galactic environment.

Critical Autonomous Technologies

The critical autonomous technologies needed to achieve both of these scenarios are **situation and self-awareness** and **collaboration and interaction**, including:

- Joint knowledge and understanding
- Event and trend identification
- Sensing and perception
- Anomaly detection

- Activity and resource planning and scheduling
- Learning and adapting
- Modeling and simulation

Those technologies will enable the following capabilities:

- Autonomous spacecraft fault detection and correction
- Onboard feature identification and downlink of interesting regions and events only
- Onboard machine learning (inference) of individual active regions to predict solar flares
- Stereographic imaging of coronal mass ejections, and autonomous detection, evaluation, and warning
- Global imagers autonomously identify ‘interesting’ regions, and direct more detailed telescopes.

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

- A testbed for simulating the constellation
- Small-spacecraft-based communication and propulsion
- Space qualified high-throughput processors
- Advanced propulsion technology (long-lasting)
- Compact instrumentation
- High-temperature-resistant materials

Findings

The Heliophysics DRM team finds the following activities would enable the mission scenarios described above:

- Developing a space weather buoy demonstration mission to orbit the Moon and serve as a gateway space weather buoy.
- Developing a testbed to assess effectiveness and return-on-investment of various Space Weather Constellation configurations.
- Developing spacecraft hardware and software fault detection and recovery
- Developing compact “smart” instrumentation
- Considering a magnetohydrodynamics modeling component as a key element of the mission
- Developing artificial intelligence/machine-learning techniques to facilitate onboard data processing and local space situational awareness

- Developing advanced observation modes and a smart downlink strategy for key measurements
- Developing autonomous fault detection and mitigation technologies for the spacecraft subsystems
- Requiring a path for flight demonstration for technologies such as computer accelerators as part of the technology readiness level (TRL) maturation

Part II: The Case for Heliophysics

Heliophysics is a discipline that is focused on understanding the formation and evolution of the solar wind and solar ejecta, and how those impact objects in the solar system, including Earth, the energization of particles, etc. Even within Earth's protective magnetic bubble, our technological society experiences impacts due to space weather. In the near future, we expect to send astronauts to the Moon and Mars. As humans leave the safety of Earth's protective magnetic bubble, they will be exposed to even harsher effects of space weather. Safeguarding human and robotic exploration and eventual colonization of the solar system is a prime motivator for this DRM.

Our vision is an interconnected network of satellites throughout the heliosphere, ground networks on other planets (e.g., radiation sensors on Mars), instruments on human spacecraft (both commercial and NASA), all autonomously connected to predictive capabilities. The system has the capability to launch 'spacecraft on demand' (e.g., from interplanetary human-carrying spacecraft) dropped as 'buoys' to monitor space weather. The system will autonomously decide to launch spacecraft, rapidly commission them, pull data from the spacecraft online, and assimilate it into space weather predictive models. Autonomous monitoring of solar active regions, coupled with models of solar eruptive events, will enable predictions that provide enough lead time to prepare for space weather impacts. Machine learning about active regions will enable flare predictions.

Part III: Design Reference Missions

DRM Scenario 1: An Autonomous Space Weather Constellation

Solar activity controls space weather in the near-Earth environment and in interplanetary space over multiple spatial and temporal scales. On timescales of minutes to hours, solar flares and energetic-particle events disturb the ionosphere/thermosphere, increase drag on satellites in low Earth orbit (LEO), disrupt global positioning systems and radio communications, and endanger astronaut safety. In less than one day, coronal mass ejections (CMEs) can impact Earth's magnetosphere, causing geomagnetic storms that can potentially disrupt power distribution over extended geographic areas. Over longer timescales, solar magnetic activity makes an imprint on space climate in terms of the average spectral solar irradiance driving

Earth's atmosphere, and in terms of the magnetic terrain that accelerates, funnels, and shapes the solar wind. Even near the solar-cycle minimum, the global magnetic field from the Sun extending into the heliosphere can result in fast solar wind structures that drive geomagnetic storms on Earth.

Improved space-weather predictions are critical to safeguarding the nation's technological assets and the safety of astronauts, whether they are in Earth orbit or en route to/from the Moon or Mars. Such improvement requires the development and validation of physics-based, data-driven numerical simulations. **This document summarizes the science case for an Autonomous Space Weather Constellation to observe the Sun from multiple vantage points and to sample solar-wind conditions from multiple locations. Required autonomy capabilities are driven by the science case.**

The current Heliophysics System Observatory (HSO) has provided unprecedented coverage of the Sun and its impact on Earth, the planets, and other small bodies (e.g., comets) in the solar system. Data from different HSO missions have been combined to help us understand (post facto) how solar activity causes space weather events. Some data exists for the development of statistical models predicting the likelihood of flares and geomagnetic storms. Furthermore, sophisticated physics-based models have been developed to model solar-wind conditions at 1 AU (including disruptions from CMEs). However, the research community and the National Oceanic and Atmospheric Administration (NOAA) are not close to providing the following types of predictions with high accuracy and confidence:

- Predict (not after the fact) whether a sunspot region will spawn CMEs, solar flares and energetic particle events in the next hours to days
- Predict the arrival time and physical properties of abrupt changes in the solar wind (including CMEs)
- Predict the geoeffectiveness (in terms of geomagnetic storm strength, e.g., *Kp* index or *Dst*) of CMEs, whether they are directed toward Earth or slightly away from Earth
- Provide an "all clear" prediction for inclement space-weather activity over the next month

While there are isolated instances of success, none of the aforementioned can be provided with reliability over a broad spectrum of solar conditions. One major reason for the lack of reliable space-weather predictions is the sparse coverage of measurements in interplanetary space at scales of 1 AU. Most HSO missions are in Earth orbit. Missions like the pair of STEREO (Solar TErrestrial RElations Observatory) spacecraft that drift around the backside of the Sun in a 1-AU orbit have demonstrated how multi-vantage point observations in the extreme ultraviolet (EUV) and white light help us pin down the source region properties of the solar wind and CMEs, and better track their propagation from Sun to Earth.

Improvements for space weather predictions are hampered by a lack of multi-vantage point observations of the Sun-Earth system:

- Currently, **only one STEREO spacecraft remains in operation**, giving us only a second vantage point to complement the perspective from the Sun-Earth/L1 line. The Parker Solar Probe does not have a remote sensing EUV imager nor a magnetograph (it does have a white light imager).

- There exists no simultaneous, 360-degree coverage of the Sun's surface magnetic field. Data-constrained and data-driven **magnetohydrodynamics (MHD) models of the Sun's coronal magnetic field and its extension into the heliosphere require full-sphere magnetic maps.** The input data currently used are so-called synoptic (but not synchronic) magnetograms composing of data collected over the Sun's rotation (about 1 rotation per month). Due to the fast emergence of sunspot groups and their more gradual disintegration, the solar magnetic field changes substantially over days and weeks. While sunspot groups appear isolated on the solar surface, they have a global influence on magnetic connectivity in the corona and heliosphere. Reliable observations of the Sun's polar fields will also improve models. At present, there is no consensus on the strength of the Sun's polar fields (uncertainty is a factor of 2 to 3). By missing one active region or by using poorly measured (inaccurate) polar fields in the boundary condition magnetic map, the 3D magnetic topology—and hence the modeled solar wind properties—can be drastically wrong. The wrong ambient magnetic topology and solar-wind structure also leads to errors in models of CME propagation.

- **The properties of CMEs, from their initial formation in the solar corona to their propagation through interplanetary space, are poorly characterized.** For most CMEs, there exists at most a single spacecraft providing in situ measurements of the magnetic field and plasma properties. Isolated measurements at Lagrangian point 1 (L1) along the Sun-Earth are too late and too few for reliable predictions with lead times exceeding one or two hours. Except in numerical models, we generally do not know how CMEs evolve as they propagate to 1 AU. Simultaneous in situ measurements over extended areas covered by a CME are needed to resolve the question of evolution and internal structuring of CMEs. To further constrain the properties of CMEs, EUV and coronagraph imagers from multiple vantage points will be needed. Data from these remote sensing instruments will allow for tomographic reconstruction of the coronal field and CME structure, which will put tighter constraints on CME orientation, speed, and direction of propagation.

- **The Autonomous Space Weather Constellation is a DRM aimed at filling the gap in our observational capabilities in order to facilitate validated, near real-time, data-driven models of the Sun's global corona, heliosphere, and associated space weather effects.** The next section outlines the concept of operations for this DRM, and how this drives the need for specific autonomy capabilities.

The Concept of Operations

To capture a broad range of solar conditions (from solar minimum to maximum, back to minimum), the DRM has a nominal mission length of 10 years.

Consider a constellation of spacecraft **S** = {S_0, S_1, …, S_n} offering a simultaneous 4$\boldsymbol{\pi}$ steradian view of the solar surface. Each spacecraft will have a different orbit. A subset of spacecraft will be placed in STEREO-like 1-AU orbits, such that they drift behind the Sun. Using n≥3 such satellites, with an angular separation of (360/n) degrees is needed to maintain consistent, continuous coverage over the length of the mission. At least two more spacecraft are needed in orbits out of the ecliptic to simultaneously observe both the north and south poles. All aforementioned spacecraft are equipped with a magnetograph, coronagraph, EUV imager, and in situ instruments. A further set of (#TBD) spacecraft with portions of orbits between 0.5 and 1.0 AU is required to provide only in situ measurements of the solar wind (and CMEs) before their arrival at Earth.

With a full suite of instruments onboard each spacecraft, the rate of data flowing into the onboard computer can easily be on the order of 100s of MB/s. The aim of the tiered storage/downlink concept is to cull the data so the required telemetry is a factor of 1000 lower. This reduction cannot be done using conventional compression alone. Various approaches are required to achieve this data rate reduction. These include:

A. Onboard data processing from observables to higher level, science quality data products (e.g., 24 Stokes polarization images to 6 atmospheric measurements by performing onboard inversions, e.g., use of a field-programmable gate array [FPGA] on Solar Orbiter's Polarimetric Magnetic Imager)
B. Data culling (data cutouts, subsampling, onboard averaging): requires onboard inference to categorize datasets
C. Compressed sensing: i.e. designing detectors so that they capture the signal in terms of specially-chosen basis functions, and downlink those sparse coefficients for reconstruction on Earth
D. Conventional lossy data compression

To enable A, the onboard computer will need the capability to process the raw data into scientifically useful higher-level observables. We assume the calibration/processing pipeline will be finalized during the commissioning phase, and then uplinked to the spacecraft. This approach requires certain flexibility in the flight software/hardware stack. It also requires efficient pipelines enabled by a combination of fast onboard central processing units/graphics processing units (CPUs/GPUs) and machine learning techniques. For instance, it has been shown that neural networks can accelerate some physics-based inversion tasks by two or three orders of magnitude (Cheung 2018; Wright 2018).

To enable B, the onboard computer will run pattern detection/classification algorithms on all data delivered from the instruments and rank the data in terms of the following metrics: (M1) urgency/pertinence for space weather predictions, (M2) relevance to intended scientific goals, and (M3) uniqueness.

- Datasets ranked highest in terms of metric (M1) will receive highest priority for downlink to a data center on Earth for immediate use by space weather stakeholders and for input to MHD models. An example of such a dataset would be EUV imager observations of a coronal mass ejection.
- Datasets ranked high in M2 and M3 will be stored in onboard memory for delayed downlink.
- Datasets ranked low in all three metrics will be discarded (neither saved nor transmitted).

The pattern detection/classification algorithms can be based on supervised or unsupervised learning on datasets taken during the commissioning period. More likely they would have been validated and tested on existing large-scale data sets (e.g., against the petabyte-scale data archive of the Solar Dynamics Observatory). We distinguish training and inference as distinct tasks. The *training* of a classification/regression model is typically computationally expensive, and depending on the problem size, requires dedicated GPU resources drawing hundreds of Watts of power. It would be unrealistic to perform such tasks onboard. However, once the model (e.g., a neural network) has been trained (i.e., network weights and biases have been fixed), the deployment of the network to perform classification/regression—a task called *inference*—requires far less computation. This is the approach of machine-learning applications deployed in embedded devices.
Capabilities C and D are not necessarily autonomous concepts/technologies but still require high-throughput onboard processing. The software stack required to facilitate A-to-D are enabling technologies for this DRM and investments in their development are just as important as for hardware.

Downlink concept: One concept for downlinking data from the constellation is peer-to-peer relay communication. This approach may be necessary to increase effective mission-wide bandwidth, maximize temporal coverage, and minimize latency. For instance, consider a spacecraft at 1 AU behind the Sun. It is not possible to directly downlink data from the satellite to a ground station on Earth. To avoid a latency of several months to send the data, this satellite can send data to a peer in the constellation. The receiving peer, with a direct line-of-sight to the ground station, can then relay the data.

Each message is considered a *Local Space Situational Awareness Memo* (LSAM). A LSAM contains the following contents:

- Sender
- Receiver
- Instrument data from different instruments, with associated priorities M1, M2 and M3
- Metadata attached to the instrument data, including reports of feature detections (e.g., coronal mass ejection found at a certain location on the Sun at a certain time)

Each satellite is an autonomous agent. The message to be sent from one satellite to another (or to the ground station) is written entirely by the sender. The receiver then must prioritize which data sets (its own, or LSAMs it received from peers) to send to the next peer and/or to the ground station. But LSAMs need not be sent purely for the purpose of downlinks. LSAMs can be sent to peers who are not close to ground stations. They can be sent for the purpose of providing global situational awareness for the peers. For example, when the front-side satellite detects an eruption toward solar north, it may notify its peers (some of whom maybe on the Sun's backside), so the peers can decide whether to allocate future telemetry and memory for observations of the northern portion of the Sun. To benefit other NASA activities each peer in the constellation can also serve as a router to facilitate downlink (e.g., to increase telemetry for planetary explorers).

Assumptions

- Sufficiently powerful antennas (radio or optical) to enable peer-to-peer communication
- Radiation hardened CPUs/GPUs/FPGAs/application-specific integrated circuits (ASICs) available for high-throughput (>1 teraflop) data processing and inference

Autonomy is needed for this DRM scenario for the following purposes:

- Maximize scientific/operational value for given telemetry
- Mission resilience: no single satellite agent failure should terminate the mission
- Provide space situational awareness in a local context, and then in a global context
- Provide data needed for a continuously driven model of the Sun and heliosphere to improve space weather predictions
- To collect data from unprecedented vantage points and unexplored regions to help us understand the Sun-to-Earth connection.

Autonomy Capabilities needed for an Autonomous Space Weather Constellation

- **Onboard decision making to effectively utilize resources (power, observing capabilities, onboard storage, telemetry).** Autonomy will help maximize scientific/operational value for given telemetry. Observed regions deemed most important for accomplishing scientific and operational space weather objectives will be prioritized for transmission to mission ground stations. This capability will provide the data needed for a continuously driven model of the Sun and heliosphere to improve space weather predictions.
- **Onboard machine-learning (inference) for local space situation awareness and to provide space weather alerts.** Each probe in the constellation must be capable of preparing its own space weather report and broadcasting the report to the constellation. This capability should improve global space weather awareness by the constellation.
- **Provide multi-vantage point data needed for a continuously driven model of the Sun and heliosphere.** Autonomy is needed to collect data from unprecedented vantage points and

unexplored regions to help us understand the Sun-to-Earth connection. The integrated space weather model should autonomously decide which data sources will be used in updating the estimated state of the Sun and heliosphere, be able to evaluate the accuracy of its own predictions, and adaptively improve. To speed up the model's improvement, there should be a mechanism by which human feedback can be accepted (i.e., an active learning feedback loop).

- **Global imagers autonomously identify 'interesting' regions, and direct more detailed telescopes.** To autonomously direct other resources, mission elements must possess space situational awareness in a global and local context.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for these capabilities are:

- *Joint knowledge and understanding:* Collection, assembly, sharing, and interpretation of information and intent among elements to solve problems and plan actions/responses.
- *State estimation and monitoring:* Estimation of internal and external states from raw or processed inputs generated by multiple sensors/instruments, ascertainment, and continual comparison to expected states.
- *Event and trend identification:* Analyses of data (about environment or system) to identify events and trends that may affect future state, operations, or decision-making.
- *Sensing and perception:* Collection and processing of information internal and external to the system from sensors and instruments.
- *Anomaly detection:* Determination that the environment or system does not exhibit expected characteristics.
- *Activity and resource planning and scheduling:* Selection and ordering of activities to be performed while managing system resources to achieve mission goals.
- *Learning and adapting:* Adapting to changing environments and conditions without explicit re-programming using knowledge collected from the past, or from other systems' experiences.
- *Modeling and simulation:* Representation of an autonomous system and/or its operation for use in system design, evaluation, or operational assessment.

Other supporting, non-autonomous technologies that are needed include small-spacecraft-based communication and propulsion, space-qualified high-throughput processors and a testbed for simulating the constellation. Even though the testbed itself is not considered autonomous technology, it drives development of the aforementioned autonomous capabilities. It is also needed to refine satellite/instrument requirements. The testbed needs the following components:

- Physics-based MHD solver(s) driven by remote-sensing and in situ observations
- Modules for synthesizing observables measured by instruments in the constellation, including instrument characteristics (e.g., telescope point spread function, particle hits on detectors, noise etc.)

- Modules for simulating onboard processing, including inference
- Module for the creation, sending, and receiving of LSAMs
- Module for autonomous decision-making by members of the constellation

DRM Scenario 2: An Interstellar Probe

From just after the beginning of the Space Age and the establishment of NASA, a mission to the Local Interstellar Medium (LISM) has been under discussion. The remarkable science opportunities that arise from such an "Interstellar Probe" traveling beyond the Sun's sphere of influence have fueled the community for almost six decades, resulting in multiple international study efforts including the Interstellar Probe (Holzer et al., 1990), the Innovative Interstellar Explorer (IIE) (Fiehler et al., 2006), NASA-funded Sun-Earth-connection Roadmap study for an Interstellar Probe mission in 1999-2000 (Liewer et al., 2000; McNutt et al., 2011; Mewaldt et al., 2001), the European-led Interstellar Heliopause (IHP) mission (Wimmer-Schweingruber et al., 2009), the Keck Institute for Space Studies Workshop series conducted in 2014 and 2015 on the topic *"Science and Enabling Technologies for the Exploration of the Interstellar Medium"* (Stone et al., 2015; Arora et al., 2015), and the "Interstellar Express: A New Chinese Space Mission to Explore the Outer Heliosphere" (Wang, 2018; Zong, 2018). Most recently, NASA funded a study of the "Pragmatic Interstellar Probe" (McNutt et al., 2019; Brandt et al., 2019; http://interstellarprobe.jhuapl.edu) which would use available/near-term technology launch vehicles and kick stages to reach asymptotic speeds at least three times that of Voyager 1, which is currently the fastest spacecraft escaping the Sun's gravity well.

Science Goal 1: Understand our heliosphere as a habitable astrosphere. Investigate the plasma physical processes and global nature of the outer heliosphere boundary and beyond to the pristine LISM through comprehensive particle and fields measurements, and remote energetic neutral atom (ENA) and ultraviolet (UV) observations.

Science Goal 2: Understand the evolutionary history of the solar system. Explore dwarf planets and Kuiper Belt Objects (KBOs) through flybys observing atmospheric and surface properties. Determine the large-scale distribution of the circum-solar debris disk by detecting the infrared (IR) emissions from dust in the 0.5-10 µm range on an outward trajectory, while measuring in situ dust densities.

Science Goal 3: Open the observational window to early galaxy and stellar formation. Measure the integrated diffuse Extragalactic Background Light (EBL) from redshifted stars and galaxies dating back to ~200 million years after the Big Bang by detecting the near-infrared emissions beyond the Zodiacal cloud.

The Interstellar Probe DRM scenario is a proposed mission to travel to the LISM and measure the environment beyond the solar system The probe would launch around 2030 and travel 20 AU/year for 50 years to reach 1000 AU. The Interstellar Probe would make comprehensive, state-of-the-art, in situ measurements of plasma and energetic-particle composition, magnetic fields, plasma waves, ionic charge states, energetic neutrals, and dust that are required for understanding the nature of the outer heliosphere and exploring our local galactic environment.

A mission beyond the Sun's sphere of influence as outlined above represents humanity's first deliberate step in to the galaxy. Beyond its transformational promise, an Interstellar Probe would be a stunning revolution in space missions demanding it to be a multi-generational facility.

The Concept of Operations

As the Interstellar Probe transits outside our solar system, the spacecraft must rely on "smart" autonomy systems on multiple spacecraft subsystems (e.g., anomaly recovery) because telecommunication capabilities will be severed degraded. In addition, the payloads must have autonomy capabilities to take advantage of unexpected observations once the spacecraft is in a new, unexplored region while utilizing a limited data downlink for science measurements.

Autonomy Capabilities needed for an Interstellar Probe

- **Autonomous spacecraft fault detection and correction.** Autonomy is needed for spacecraft hardware and software fault detection and recovery. As the Interstellar Probe transits to the outer heliosphere and even beyond the solar system, the real-time commanding of both the spacecraft and payloads will be severely limited and not feasible due to the increased time required to transmit commands over increasingly long distances. Hence, it is essential that the spacecraft should have autonomous fault detection and correction capability because it will be on its own once it travels beyond the real-time commanding region.
- **Smart-instrument data taking.** The science telemetry will be severely limited, hence a uniform data-collection strategy (i.e., constant rate) may not be the best observation plan, especially when the spacecraft transits some unforeseen interesting regions (e.g., heliopause). Hence the instrument must be "smart" enough to switch to a higher data rate once it detects an interesting region.
- **Onboard feature identification and prioritization.** Similar to the Space Weather Constellation DRM, the Interstellar Probe mission will also require some type of onboard feature identification capability in conjunction with the smart-instrument data taking. The combination of the two advancements in autonomous technology will mitigate risk and enable the mission.

The autonomous technologies needed for this capability include:

- Spacecraft hardware fault detection and recovery
- Spacecraft software fault detection and recovery
- Smart instrument data taking system
- Onboard feature identification and prioritized downlink
- Autonomous spacecraft fault detection
- Autonomous instrument mode switching

The following additional technologies (not related to autonomy) are also needed to support this mission scenario:

- Advanced propulsion
- Advanced communication
- Heat shield
- Lightweight material
- Compact instrumentation

The Relevant Research and Development Projects for these DRMs

- NASA Frontier Development Lab projects that apply AI techniques for accelerated processing of existing Heliophysics data (e.g., SDO images)
- Raising TRLs of low-power compute accelerators (e.g. GPUs, neuromorphic chips, FPGAs)
- R&D project to develop a testbed to quantify the performance of different constellation configurations (i.e., number of probes, how many remote sensing instruments, which orbits)
- Raising TRLs of optical satellite communications to increase telemetry

The Potential Challenges, Risks, or Questions for these DRMs

- Keeping costs down
- Reduces ground operations costs and improves resiliency
- Question about whether small spacecraft can carry the payloads (100-200 kg class satellite can carry one, perhaps two remote sensing instruments—more if in situ).
- Reduce risk to astronauts, particularly for spacewalks and Mars surface exploration
- Path for maturing the technologies for flight
- Flagship mission that will require agency resources and commitment
- Require multi-year commitment
- Path for TRL maturation

Part IV: Findings

The Heliophysics DRM team finds the following activities would enable the mission scenarios in this DRM:

- Developing a space weather buoy demonstration mission to orbit the Moon and serve as a gateway space weather buoy
- Developing a testbed to assess effectiveness and return-on-investment of various Space Weather Constellation configurations

- Considering a magnetohydrodynamics modeling component as a key element of the mission
- Developing spacecraft hardware and software fault detection and recovery
- Developing compact “smart” instrumentation
- Developing artificial intelligence/machine-learning techniques to facilitate onboard data processing and local space situational awareness
- Developing advanced observation modes and a smart downlink strategy for key measurements
- Developing autonomous fault detection and mitigation technologies for the spacecraft subsystems
- Requiring a path for flight demonstration for technologies such as computer accelerators as part of the technology readiness level (TRL) maturation

Part V: Heliophysics DRM Team

The Heliophysics Design Reference Mission team is comprised of:

- **Larry Kepko**, NASA GSFC
- **George Ho**, Johns Hopkins University APL
- **Mark Cheung**, Lockheed Martin Solar & Astrophysics Laboratory

Part VI: References

Arora, N., Strange, N., & Alkalai, L. (2015). Trajectories for a near term mission to the interstellar medium.

Brandt, P. C., et al. "Humanity’s first explicit step In reaching another star: The Interstellar Probe mission." *Journal of the British Interplanetary Society*, submitted (2019).

Cheung, M. C. M., “Deep Learning for Heliophysics”, NVIDIA GPU Tech Conference 2018, San Jose, CA, USA, http://on-demand-gtc.gputechconf.com/gtc-quicklink/atho3n8.

Holzer et al., (1990), The Interstellar Probe: Scientific Objectives and Requirements for a Frontier Mission to the Heliospheric Boundary and Interstellar Space, Interstellar Probe Workshop, Ballstron VA, March 20-21, 1990

Fiehler, D. I., & McNutt Jr, R. L. (2006). Mission design for the innovative interstellar explorer vision mission. *Journal of spacecraft and rockets*, 43(6), 1239-1247.

Johns Hopkins Applied Physics Laboratory, "Interstellar Probe," Accessed January 31, 2020, http://interstellarprobe.jhuapl.edu.

Liewer, P. C., Mewaldt, R. A., Ayon, J. A., & Wallace, R. A. (2000, January). NASA's interstellar probe mission. In *AIP Conference Proceedings* (Vol. 504, No. 1, pp. 911-916). American Institute of Physics.

McNutt Jr, R. L., & Wimmer-Schweingruber, R. F. (2011). Enabling interstellar probe. *Acta Astronautica*, 68(7-8), 790-801.

McNutt Jr, Ralph L., et al. Near-term interstellar probe: First step. *Acta Astronautica* 162 (2019): 284-299.

Mewaldt, R. A., Liewer, P. C., Mewaldt, R., Liewer, P., Bakes, E., Frisch, P., and Kurth, W. (2001, January). Scientific payload for an Interstellar Probe mission. In *COSPAR Colloquia Series* (Vol. 11, No. C, pp. 451-464). Elsevier Masson SAS.

McNutt Jr, R. L., Gold, R. E., Krimigis, T., Roelof, E. C., Gruntman, M., Gloeckler, G., and Horanyi, M. (2006, September). Innovative interstellar explorer. In *AIP Conference Proceedings* (Vol. 858, No. 1, pp. 341-347). American Institute of Physics.

Stone, E. C., Alkalai, L., & Freedman, L. (2015). Science and Enabling Technologies to Explore the Interstellar Medium.

Wimmer-Schweingruber, R. F., & McNutt, R. (2009). The Interstellar Heliopause Probe: Heliospheric Boundary Explorer Mission to the Interstellar Medium. Earth, Moon, and Planets, 104(1-4), 17-24.

Wang, C., & Li, H. (2018, December). Interstellar Express: A New Chinese Space Mission to Explore the Outer Heliosphere. In *AGU Fall Meeting Abstracts*.

Wright, P., et al., "DeepEM: A Deep Learning Approach for DEM Inversions", Chapter in the e-book "Machine Learning, Statistics, and Data Mining for Heliophysics" by M. Bobra & J. Mason, 2018, https://helioml.github.io/HelioML/04/Differential_Emission_Measurements.

Zong, Qiugang. Interstellar Heliosphere Probes (IHPs). 42nd COSPAR Scientific Assembly. Vol. 42. 2018.

The Mars Design Reference Mission Report

Part I: Abstract

Mars is special. It is our closest planetary neighbor and shares commonalities with Earth. NASA has studied Mars more than any other solar system object outside the Earth and Moon. The scientific exploration of Earth's planetary neighbor has largely focused on addressing the presence and persistence of water, geochemistry, geology, and atmospheric evolution. Prior, current, and near-term missions are filling in fundamental Mars knowledge gaps and in doing so, support models of how the Mars planetary system functions and has evolved. These missions also take the first steps necessary for addressing whether or not Mars ever hosted microbial life. However, in situ data collections are limited to singular spacecraft in singular

localities. All but one (the European Space Agency's ExoMars mission) are largely limited to a surface investigation. Past, current, and near-term mission architectures, while critical for exploration on a broad scale via multiple missions, do not support the system-level understanding of processes and conditions at regional scales.
The time has come for a paradigm shift. Sustained, wide-area study is needed to take the next step: to explore Mars as a system. This document describes not a single mission, but a practical, scalable and sustainable **Mars Exploration Campaign** that establishes an exploration framework on Mars. In this framework, new spacecraft, new rovers, and missions themselves become new elements within the campaign's framework.

Mars is expected to be the first destination for humans beyond the Moon. The human exploration zone will be regional in scale (~100-km radius). It is expected that humans will investigate, utilize in situ resources, and change the environment at this scale. Establishing in-depth knowledge of the surrounding environment, from subsurface to atmosphere, may be critical to the success of human missions at Mars. This Design Reference Mission (DRM) describes a practical mission that precedes human exploration and provides a detailed reconnaissance survey that will support initial human activities and provide an informational, infrastructural, and operational foundation for sustained human-robotic activities. The infrastructure is scalable (spatial), mission-extendable (time), and extensible to other missions (integration and growth).

As the foundational mission in the Mars Exploration Campaign, this Mars DRM aims to study the ground-water ice in the context of climate and regional geology, local weather, and possible biology while also providing detailed insight on the location and potential exploitation of subsurface water on Mars. These aims address ***NASA's 2018 strategic plan*** [1] by specifically addressing: Objective 1.1 to understand the Solar System, in particular with respect to searching for life elsewhere; preparing for Objective 2.2 to "conduct human exploration in Deep Space…"; and Object 4.6 paving a path forward to establishing sustainable infrastructure capabilities and operations on Mars. The DRM also addresses the three high-priority science goals for the exploration of Mars as described in the current ***Planetary Decadal Survey [2]***: "Understand the processes and history of climate," "Determine if life ever arose on Mars," and "Determine the evolution of the surface and interior." The crosscutting nature of this DRM effectively addresses all four goals of the ***Mars Exploration Program Analysis Group's 2015 goals document [3]***.

The investigation is not possible without substantial developments in autonomy. The sheer area involved requires many surface assets, including rovers, helicopters, and fixed landers. Each asset cannot wait for an Earth-based team to provide daily instructions on where to move, which targets to select, and whether or not the target is of interest. In particular, this investigation requires surface navigation, individual-agent planning, multi-agent planning, and automated science analysis.

Comparison to State of the Art

Mars rovers to date have used onboard stereo vision to detect and avoid obstacles and to do visual dead reckoning of their position relative to the start of each drive. At the end of each Mars day ("sol"), the rover position relative to orbiter imagery has been estimated by human operators, who manually register downlinked images from the rovers to orbiter images. The 2020 Mars rover is expected to be able to drive up to about 300 meters per sol, using a new computer vision coprocessor to accelerate obstacle detection and visual dead reckoning. The total rover traverse objective for the 2020 mission, including time spent on science operations, is to cover about 20 km in 1.5 Mars years (about 2.8 Earth years). For comparison, the Opportunity rover, which landed on Mars in 2004, drove a total of about 45 km in about 14 Earth years. The 2020 Mars mission plans to carry a 2 kg helicopter to conduct the first ever technology demonstration of a heavier-than-air aircraft on another planet. If successful, this helicopter will execute about 5 flights, up to on the order of 100 m long.

Driving and flight distances are constrained by the power required for mobility and by the amount of energy available per sol from onboard solar arrays or radioisotope power systems. For future missions, energy-limited traverse distances on the order of 1 km/sol or more may be possible. The Curiosity rover, which landed in 2012, on average has driven on approximately one third of the sols in the mission; non-driving sols were spent on a variety of functions, including science operations.

Autonomous vehicles on Earth can operate much faster than vehicles on Mars, but have access to much more energy, such as hydrocarbon fuels that are manually replenished, and use non-space-qualified onboard computers that have much higher performance than is available now for spacecraft. This and other factors make direct performance comparisons of Earth and Mars vehicles of limited value.

In the area of intelligent science instruments or "autonomous science," only relatively limited demonstrations of onboard autonomy have been done, such as automatic detection of clouds and dust devils [10]. Some instruments contain simple optimization algorithms. The Sample Analysis at Mars instrument on the Mars Science Laboratory contains such an algorithm. However, these simple algorithms do not constitute autonomy. The value to NASA of science autonomy will become enormous over time. Current science analysis on all missions to Mars, including Mars 2020 and ExoMars 2020, relies on relaying complete science data to Earth for analysis where a large team of scientists manually evaluates the data and makes decisions about the next steps for the mission. This approach creates a data volume limitation. In 2021 three rovers may be operating on Mars with as many as four (Mars Reconnaissance Orbiter [MRO], MarsExpress, Mars Atmosphere and Volatile EvolutioN [MAVEN] and Trace Gas Orbiter [TGO]) relay satellites transmitting data to Earth and yet each mission is bandwidth limited.

Findings

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

- Embrace the paradigm of **Exploration Campaigns** with a scalable network of cooperating, independent assets.
- Continue to develop **autonomous navigation and operation skills**, such as the ability to drill and handle samples. This technology cuts across almost any robotic planetary mission.
- Develop artificial intelligence techniques for **in situ science data analysis** for each type of instrument expected to be deployed on Mars or other planetary missions.
- Immediately start developing very small, low powered, **peer-to-peer interface standards** for multiple agents.
- Develop much **more powerful spaceflight compatible computing** platforms. Make base ship platform capable of performing the equivalent of “cloud” computing services for surface assets.
- Develop artificial intelligence **techniques to monitor health of surface assets** to identify and work around faults for reduced risk and increased operational efficiency.

Part II: The Case for Mars

Introduction

This Mars DRM aims to study the ground-water ice in the context of climate and regional geology, local weather, and biology while also providing detailed insight on the location and potential exploitation of subsurface water on Mars.

Why Mars?

Mars is considered a possible abode for past, modern, and future (human) life. As such, it is a key planetary target for exploration. ***From an astrobiological perspective***, Mars may have hosted ancient microbial life when the planet was warmer and wetter than today and it is possible that microbial life persists on modern (last 5 million years to present) Mars in the subsurface, away from the intense ionizing radiation and dryness of the surface. Models indicate that the obliquity cycle of Mars has a significant influence on the climate and geohydrology of the planet, such that mid- to high-latitude near-subsurface ice (several meters) may have been flowing ground water during times of high obliquity [4, 5, 6]. Furthermore, between wet periods, the ground ice can be lost to sublimation or can be mixed with other materials by periglacial freeze/thaw churning of near surface sediments [7, 8, 9]. ***From a Mars system perspective***, piecing together the reservoirs and dynamics of the Mars climate and its hydrologic cycles is critical to understanding planetary evolution, atmospheric composition, where water resources are most likely concentrated, and even the modern-day surface conditions (e.g., frost formation, near-surface moisture mobility, salt distribution, static charge). ***From a human exploration perspective***, water resources may fulfill a critical resource need for humans and their habitat, and present potential hazards such as biology or high salt concentrations. What is more, determining the physical and chemical properties of subsurface water, its distribution and mobility, and its biological potential may influence human activities.

Humans will change the Mars environment at least on a local scale if not a regional scale, and they will need to monitor this change for the sake of science and to also mitigate risks to human safety and equipment longevity. This requires a fundamental understanding of the Mars surface and near-subsurface prior to direct human influence. Robotic missions may fill this knowledge gap, but an array of mobile platforms is necessary to cover regions on the scale of a human exploration zone (100-km radius).

DRM Science Objectives

There are three overarching objectives of the DRM. Addressing these objectives will enable scientists to answer key science questions.

Objective 1: Determine the distribution and physical context of subsurface (0-5 m) water at regional scale (approximately a 100-km radius).

a. Does the in situ map corroborate remote sensing water maps?
b. Is it primarily pore ice, layered-ice, icy regolith, or mineral hydration?
c. Is the presence or nature of water related to geomorphic and other geological features within the study region? What is the nature of the water reservoir?
d. What processes and sources are responsible for water detected? Do they reveal anything about changes in climate with respect to obliquity?

Objective 2: Determine subsurface physical, chemical, and biological water qualities

a. What is the water activity, Eh, and pH?
b. What is the composition of impurities? Do they support habitability?
c. Is there any indication of recent biology in the water? Recent biology includes extant life and dead organisms that may be recorded in ice since the last thawing, as these two groups will have the greatest impact on future missions.

Objective 3: Monitor weather conditions at regional scale.

a. How do surface environmental conditions (temperature, humidity, wind, radiation) affect the physical state of the subsurface water?

These objectives might also support human exploration interest in knowing where the best places are for accessing subsurface water in the actual exploration zone (if humans go to the same region) or in an analogous site; what to expect in terms of water qualities that pose advantages and disadvantages to human activities; meteorology data that might be relevant to human missions; and an understanding of effects of meteorological conditions on subsurface water or water brought to the surface for use.

Part III: Design Reference Mission Scenario

A Mars Subsurface Geohydrology Investigation

As the first stage of the Mars Exploration Campaign, the science-motivated Mars Subsurface Geohydrology Investigation will consist of multiple missions to Mars in order to survey on the scale required. Each mission consists of several surface assets. We conceive the first mission to use a small number of assets with a target zone of tens of square kilometers. The number of assets will be scaled up at each mission until sufficient assets are in place to meet the objectives and complete a detailed geohydrology map on the scale of the human exploration zone.

The Concept of Operations

The concept of operations for the Mars Subsurface Geohydrology Investigation consists of a fleet of small rovers, helicopters and a fixed lander.

Each rover contains instruments capable of providing: ice and hydrated mineral measurements; subsurface sounding measurements, such as ground penetrating radar; ice solute composition measurements, such as Phoenix Ion Selective Electrodes (ISE); drilling and sample acquisition; weather measurements; imagers for surface feature detection and navigation; and, communication with other surface assets and orbiters. Each rover is also capable of caching samples and delivering them to the fixed lander, or eventually to a human base station.

Small, independent helicopters provide aerial atmospheric measurements and surface imagery. Weather measurements at altitude complement surface measurements and enhance the understanding of Martian water system and weather patterns. Note that the helicopters may not be used if the selected exploration zone is at relatively high altitude.

The fixed lander, or “base ship,” contains a laboratory of instruments to perform a detailed analysis of samples delivered by the rover fleet. It has robust communication with orbiting assets as well as direct communication with Earth. Instruments onboard the base ship are capable of biosignature detection. The base ship also contains a powerful computer capable of supporting neural networks.

The rovers use the base ship’s computing ability for detailed analysis as they perform field sample collections. Rovers transmit instrument science data to the base ship where the computer’s neural networks analyze the data to identify the fundamental composition of the sample. This high-level science information is useful for three purposes:

- The rovers’ instruments use this information to determine how they should tune themselves and whether the sample requires further analysis.
- The fundamental composition results are automatically integrated into the geohydrology map.
- Fundamental composition results are transmitted to Earth rather than the complete science data set from each rover, dramatically reducing data volume. Science team can selectively request supporting data for the most interesting results.

Rovers traverse outward from the landing site in a cooperative search pattern. Samples are drilled at intervals and at likely places based on geology, surface features, and information from remote sensing water maps. As the mission progresses, science teams on Earth use the growing subsurface geohydrology map along with weather data to refine the description of likely places for drilling and gain a better understanding of the global Mars system.

Assumption(s)

There will be a few assumptions for this mission:

- Orbiters will be in place to support surface communications with Earth.
- Computing power for surface assets will be powerful enough to perform neural network algorithms.
- Tactical planning will be performed in situ on Mars, strategic planning will be done from Earth.
- Hardware to support relatively high-bandwidth peer-to-peer communications on the surface at rates on the order of 5Mbits/second.
- More energy will be available to rovers either through reduced power needs for mobility or improved solar or other energy production methods.
- Lightweight drilling systems capable of delivering samples from 1-5 meters below the surface.
- Advances in ground-penetrating radar and magnetic induction spectrometry to identify subsurface water and quantify the state of the water as liquid, ice, or within a clay mineral.

Autonomy is needed for this DRM for the following purposes:

A. Individual Agent Task Planning
B. Collaborative Multi-agent Task Planning
C. Sample Acquisition and Delivery
D. Surface Navigation
E. Scientific Autonomy

Each of these items is described in detail below. The autonomous technologies needed for this DRM are summarized in the following table, using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a guide.

Capability	Functionality	Autonomous System Taxonomy
Individual Agent Task Planning	Collection and processing of information internal and external to the system from sensors and instruments.	*Sensing and perception*
	Selection of goals, objectives, and activities to achieve a mission, subject to the situation and constraints.	*Mission planning and scheduling*
	Selection and ordering of activities to be performed while managing system resources to achieve mission goals.	*Activity and resource planning*
	Agreement on current and future activities, their priorities, and their disposition among elements or systems.	*Goal and task negotiation*
	Change of system state to meet mission goals and objectives according to a plan or schedule, subject to	*Execution and control*

	control authority and permission and based on mission phase, environment, or system state.	
Collaborative Multi-agent Task Planning	Agreement on current and future activities, their priorities, and their disposition among elements or systems	*Goal and task negotiation*
	Collection, assembly, sharing, and interpretation of information and intent among elements to solve problems and plan actions/responses.	*Joint knowledge and understanding*
	Estimation of internal and external states from raw or processed inputs generated by multiple sensors/instruments, ascertainment, and continual comparison to expected states.	*State estimation and monitoring*
	Selection of goals, objectives, and activities to achieve a mission, subject to the situation and constraints.	*Mission planning and scheduling*
	Selection and ordering of activities to be performed while managing system resources to achieve mission goals.	*Activity and resource planning and scheduling*
	Change of system state to meet mission goals and objectives according to a plan or schedule, subject to control authority and permission and based on mission phase, environment, or system state.	*Execution and control*
	Assurance that the system is operating in a manner consistent with expectations of all elements.	*Operational trust building*
Sample Acquisition and Delivery	Collection and processing of information internal and external to the system from sensors and instruments.	*Sensing and Perception*
	Creation of information sources about the environment or the system from sensing, perception, and human interaction that can be queried.	*Knowledge and Model Building*
	Evaluation of whether the state of the environment, the state of the system, and/or their interaction pose a threat to the safety of actions (or inactions) that are contemplated, which could compromise the system or mission.	*Hazard Assessment*
	Analyses of data (about environment or system) to identify events and trends that may affect future state, operations, or decision-making.	*Event and Trend Identification*
	Determination that the environment or system does not exhibit expected characteristics.	*Anomaly Detection*
	Selection of goals, objectives, and activities to achieve a mission, subject to the situation and constraints.	*Mission Planning and Scheduling*
	Selection and ordering of activities to be performed while managing system resources to achieve mission goals.	*Activity and Resource Planning and Scheduling*
	Generation or modification of a path or trajectory to reach a desired target physical location or configuration, subject to system and environment constraints.	*Motion Planning*

	Change of system state to meet mission goals and objectives according to a plan or schedule, subject to control authority and permission and based on mission phase, environment, or system state.	*Execution and Control*
	Identification of faults, prediction of future faults, and assessment of system capability as a consequence of those faults.	*Fault Diagnosis and Prognosis*
	Restoration of nominal or best-possible system configuration and operations after a fault.	*Fault Response*
	Adapting to changing environments and conditions without explicit re-programming, using knowledge collected from the past or from other systems' experiences.	*Learning and Adapting*
Surface Navigation	Generation or modification of a path or trajectory to reach a desired target physical location or configuration, subject to system and environment constraints.	*Motion Planning*
	Change of system state to meet mission goals and objectives according to a plan or schedule, subject to control authority and permission and based on mission phase, environment or system state.	*Execution and Control*
	Adapting to changing environments and conditions without explicit re-programming, using knowledge collected from the past or from other systems' experiences.	*Learning and Adapting*
	Creation of information sources about the environment or the system from sensing, perception, and human interaction that can be queried.	*Knowledge and Model Building*
	Estimation of internal and external states from raw or processed inputs generated by multiple sensors/instruments, ascertainment, and continual comparison to expected states.	*State Estimation and Monitoring*
	Collection and processing of information internal and external to the system from sensors and instruments.	*Sensing and Perception*
Scientific Autonomy	In situ calibration and parameter-setting for instrumentation.	*Learning and adapting.*
	Assessment of measurement quality.	*State estimation and monitoring*
	Automated target selection for sampling.	*Reasoning and Acting.*

A. Individual Agent Task Planning

This individual rover should be able to inspect its surroundings, identify a target location to study, and determine if the science data is sufficient or if another target should be identified and analyzed. This would an enabling technology.

A first requirement is a framework for specifying the rover's high-level mission for the duration of its autonomous operation, as determined by a combination of the base ship, orbiter, and Earth. From this high-level specification (e.g., map certain area), the rover should be able to autonomously select its lower-level objectives and activities (including both those necessary for the mission and its own continued operation). The basis of such planning will be the rover's model of its current state and interpretation of its scientific measurements, the latter of which requires new techniques for processing raw data into intelligible and actionable observations. The rover must periodically re-evaluate its plan and schedule in the face of new information, and be able to respond immediately to urgent situations such as system failures and transient events of interest.

B. Collaborative Multi-Agent Task Planning

The individual agents need to cooperate to efficiently implement a larger plan and automatically adjust the plan based on new data (e.g., maintaining an overall map and selecting targets for each agent based on minimum movement or based on expectation of findings). This would be an enabling technology.

With a heterogeneous team of rovers and helicopters, one of the first collaborative tasks to be performed will be high-resolution mapping by the helicopters. This mapping activity will determine terrain trafficability for rovers with a spatial resolution at least an order of magnitude better than is possible from orbit. Cameras on the helicopters will be able to obtain millimeter-scale imagery, which can be analyzed by neural network algorithms on the lander or even onboard the helicopters to identify stratigraphic formations of scientific interest. It may also be possible for helicopters to carry spectral instruments to do some mineralogical characterization, or miniature neutron spectrometers to measure shallow subsurface bulk hydrogen content. Helicopters will also perform basic meteorological measurements.

The initial helicopter mission will be planned using regional map information from orbiters. Higher-resolution map information collected by helicopters will be integrated on the lander. The integrated map will be used to refine and extend helicopter mission plans and to create rover mission plans. As further mapping and science information is integrated from the rover(s), that will also affect subsequent rover mission planning. The rate of progress of individual rovers will depend on science opportunities and results that are discovered on the way, so plans for each rover may be affected by progress and discoveries made by the others.

Other non-autonomous technologies that are needed include delay-tolerant networking (DTN), mesh networking, peer-to-peer interface standards for multiple interacting agents, and high-performance, remote computing.

C. Sample Acquisition and Delivery

Section E "Scientific Autonomy" describes instruments capable of subsurface water detection that provide the rover with a likely location and depth to drill for a sample. Section D "Surface Navigation" describes how the rover approaches the drill location. This section describes the technology to safely operate the drill, manipulate samples returned by the drill, and deliver the samples to the instruments within the same agent or on another agent.

Automated sample collection and manipulation require hazard assessment, anomaly detection, sensing and perception, and self-awareness.

Subsurface obstacles such as a hard rock could damage or permanently disable a drill. Onboard analysis of the subsurface instrument data allows the agent to assess the hazard to the drill. During drilling operations, anomaly detection is required to reduce damage and prevent jamming the drill into unexpectedly hard rock. A machine-learning algorithm resident on the base ship combines the subsurface data with past drill performance (of all mobile agents) to improve identification of hazardous subsurface materials as the mission progresses.

The rovers must know their location with respect to the base ship for the sample handoff. Section D, "Surface Navigation," describes the means to navigate to the base ship. The handoff of the sample will be done using image analysis of the base ship's sample receptacle, specifically designed for visual identification.

Other non-autonomous technologies that are needed include a lightweight drill capable of 5 m (TBR); sample collection capability, the handoff of potentially wet samples to the base ship, ground-penetrating radar and magnetic induction spectroscopy tuned for water detection, and sample mass or volume verification.

D. Surface Navigation

Each individual agent traverses an area to a target specified by the plan. The agent determines the best route and avoids obstacles to reach the target with the optimum route based on risk, time and energy. This would be an enabling technology.

Navigation functions include state estimation, terrain perception, and path planning. State variables to be estimated include the position, velocity, heading, and tilt of rovers, plus the altitude of helicopters. Most of these variables will be estimated using a combination of visual and inertial measurements plus wheel odometry for rovers and altimeters for helicopters. The position of all vehicles relative to regional maps created from orbiter images will be measured by corresponding features seen in images onboard the vehicles and in orbital imagery. Tilt and heading measurements may also be obtained by imaging the Sun or by recognizing landmark features on the horizon. The lander will maintain knowledge of the position of all vehicles and landmark features. The lander may detect when the same landmarks are visible to more than one platform and perform a joint optimization of the landmark and multiple vehicle positions.

Terrain perception includes perceiving the geometry of the terrain, as in creating digital elevation maps, and estimating other physical properties relevant to trafficability, such as parameters like soil cohesion that affect rover slip. Trafficability parameters that are determined by direct contact with the terrain can be associated with the geometry (e.g., slope) and appearance (e.g., texture) of the terrain, so that it will be possible to predict soil parameters ahead of rovers based on the geometry and appearance of the terrain. This form of learning and adaptation may be generalized; for example, if it is possible to associate learned soil parameters with terrain appearance in orbital imagery, and thereby to propagate locally-learned trafficability inferences to the entire region covered by the orbital imagery.

Motion planning will start with the map available from orbiter knowledge and will be revised as better map knowledge is accumulated from helicopters and rovers. Inferences about trafficability, such as parameters affecting slip, will be uncertain, so both the terrain representation and the motion planning algorithms will need to model and reason about such uncertainty.

E. Scientific Autonomy

Instruments on this mission require onboard intelligence. Subsurface instruments such as ground penetrating radar need to identify likely locations for subsurface water, identify rocks that might damage the drill, and know when water is not likely in the area being studied. In addition, instruments on each rover or the base ship need to analyze samples drilled from several meters below the Martian surface. The instruments will characterize any ice found in the sample, as well as identify minerology and signs of recent life (see the DRM Science Objectives outlined in Part II).

Time and bandwidth requirements require that the individual rovers' science instruments be intelligent, thus this is an enabling technology. Scientific autonomy, or the ability to analyze the science data in situ, will be required for three purposes:

1. The science instruments need to be able to adjust and tune themselves based on data. If the instruments see something of interest in the data, they should be able to adjust themselves without a human in the loop to further analyze the target.
2. The high rate of target acquisition and analysis on multiple-surface assets will result in data volumes too high to return to Earth. Science instruments need to reduce data volume by identifying interesting data and culling uninteresting data.
3. The instruments should provide decisional information to the local rover and the larger network of assets to determine future targets. This information may influence the decision to move, search out a new location, or to drill deeper for another sample.

Instruments capable of the detailed analysis of samples required by this mission will have numerous tunable parameters. A typical analysis experiment would start with a survey experiment where the contents of the sample are entirely unknown, and the instrument's parameters are configured for a wide range. Follow-on experiments may then be performed to provide more detail or confirm autonomously derived hypotheses.

In this DRM, the instruments send the results of the survey experiment data to the base ship for analysis. The base ship analyzes the data using its knowledge of other samples, potentially from other rovers, and responds to the rover with a set of further experiments to be performed on the sample. The rover tunes its own parameters to implement the experiments suggested by the base ship. It may need to verify the existence of particular constituents, or more accurately measure a quantity, or possibly discard the sample and either drill to a different depth or move to a new location. The base ship's analysis may illicit more than one detailed analysis experiment.

Instruments can be expected to generate large amounts of data. Several rovers working independently and at several times the speed of current rovers make it impossible to transmit all the science data back to Earth. This scenario requires the basic decision-making ability to understand what data is worth sending back to Earth when bandwidth is limited.

Commercial activity in the realm of automated science data analysis is too focused to be applicable to the discovery-driven science necessary for this mission. Also, approaches to autonomy will be unique to each class of instrument. For instance, a completely different learning algorithm will have to be applied to mass spectrometer data than to a Laser Induced Breakdown Spectrometer.

Other non-autonomous Technologies

Other non-autonomous technologies that are needed include surface-imaging computing into the Digital Terrain and Geology Map (DTGM), high-performance computing power, in situ sub-surface structure remote sensing at rover scale for integration with DTGM for 3-D models, an onboard spectral analysis to mineralogical content, and an onboard interest operator to analyze, prioritize, and decide next activity especially for transient events.

Relevant Research and Development projects for this Mars Subsurface Geohydrology Investigation DRM

Develop an integration and test approach for each system of autonomy above, including independent safety management at a “do-no-harm” level.

Develop calibration plans for science instruments centered around creating large data sets explicitly designed to train machine learning algorithms.

Part IV: Findings

The cost of developing the autonomy technologies described in this DRM are enormous. Yet the cost of not developing them is even larger. The increased science return on any planetary mission, not just missions to Mars, vastly outweighs the cost of developing these technologies. Autonomy increases the rate of science collection, improves the quality of science data, and ensures the data returned to Earth includes the most interesting science information. Once the autonomy technology is developed on the ground, Mars is the place to prove it out and then it can be applied to many planetary mission scenarios, such as missions to hostile environments like Venus or Europa.

While vast resources are being committed commercially to similar problems, commercial developments in autonomy assume powerful computers and high-bandwidth connections to an essentially limitless Internet of support. These assumptions do not apply to NASA planetary missions, including this DRM. Investments should be made to fill in the gap between what the commercial companies are doing and what is possible on planetary missions.

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

- Embrace the paradigm of **Exploration Campaigns** with a scalable network of cooperating, independent assets.
- Continue to **develop autonomous navigation and operation skills**, such as the ability to drill and handle samples. This technology cuts across almost any robotic planetary mission.
- Develop artificial intelligence techniques for **in situ science data analysis** for each type of instrument expected to be deployed on Mars or other planetary missions.
- Immediately start developing very small, low powered, **peer-to-peer interface standards** for multiple agents.
- Develop much more **powerful spaceflight-compatible computing platforms**. Make the base ship platform capable of performing the equivalent of "cloud" computing services for surface assets.
- Develop artificial intelligence techniques to **monitor health of surface assets** to identify and work around faults to reduce risk and increase operational efficiency.

Why is this DRM important?

The **Mars Exploration Campaign** paradigm defined in this DRM is a blueprint not only for Mars exploration, but exploration of most planetary targets. Once developed, the technologies of autonomous navigation, cooperation among a team of independent assets, and science autonomy will be enabling to any planetary mission.

Mars represents the best place to establish these technologies. NASA has a generation of experience in robotic operations on Mars. The environment and terrain are well known. Yet each mission raises more questions than it answers. Humans may someday help answer these questions, but they will need enormous support to do so. This DRM provides crucial data to support human life on Mars, such as the location and nature of in situ resource. It also provides a framework for human-robotic interaction once humans do arrive.

Part V: Mars DRM Team

The Mars Design Reference Mission team is comprised of:

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Part VI: References

1. National Aeronautics and Space Administration, Developed by the Strategic Investments Division (2018) NASA_2018_Strategic_Plan. 1–64.
2. National Research Council. 2011. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13117.
3. MEPAG (2018), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2018. D. Banfield, ed., 81 p. white paper posted October, 2018 by the Mars Exploration Program Analysis Group (MEPAG) at https://mepag.jpl.nasa.gov/reports.cfm.
4. Laskar, J., Levrard, B., and Mustard, J.F. (2002) Orbital Forcing of the Martian Polar Layered Deposits. Nature 419: 375–77.
5. Richardson, M.I., and Mischna, M.A. (2005) Long-Term Evolution of Transient Liquid Water on Mars. Journal of Geophysical Research 110 (E3): E03003.
6. Zent, A. (2008) A Historical Search for Habitable Ice at the PHX Landing Site. Icarus 196 (2): 385–408.
7. Mellon M. T., Malin M. C., Arvidson R. E., Searls M. L., Sizemore H. G., Heet T. L., Lemmon M. T., Keller H. U. and Marshall J. (2009) The periglacial landscape at the Phoenix landing site. *J. Geophys. Res.* **114**, E02S02.
8. Jawin E. R., Head J. W. and Marchant D. R. (2018) Transient post-glacial processes on Mars: Geomorphologic evidence for a paraglacial period. *Icarus* **309**, 187–206.
9. Soare R. J., Conway S. J. and Dohm J. M. (2014) Possible ice-wedge polygons and recent landscape modification by “wet” periglacial processes in and around the Argyre impact basin, Mars. *Icarus* **233**, 214–228.
10. Castano, A., Fukunaga, A., et al. (2006) Autonomous Detection of Dust Devils and Clouds on Mars. IEEE International Conference on Image Processing

The Moon Design Reference Missions Report

Part I: Abstract

The Moon—the cornerstone of the solar system—is an ideal exploration target for humans and robotic explorers. The Moon provides a cornerstone upon which our understanding of many planetary processes is based. From the results of prior and ongoing missions, we have proved

that the Moon is an attainable, interesting, and useful location—while confirming our understanding that there is still more to learn and explore. In particular, the Lunar Reconnaissance Orbiter (still operating in lunar orbit) has produced considerable advances in our understanding of how planets evolve, the impact cratering process, the evolution of volcanism, and how the space environment alters the surface. Future missions to the lunar surface will provide much-needed ground truth to tie together and relate some of the remotely sensed data products collected over the past several decades.

Autonomy can greatly enhance future exploration missions to the lunar surface as well as enable operations in extreme environments. Without autonomy, humans and robotic spacecraft have successfully navigated satellites, performed soft landings, deployed instruments, and returned samples to the Earth. With autonomy, future missions will have the ability to make mission-critical decisions such as those required to navigate and avoid hazards without the need for human interaction. This capability will enable the exploration of more extreme environments, reduce the delay in decision-making, and decrease the overall cost of mission operations. As the most accessible target in our solar system, the Moon is an ideal location to demonstrate new technologies. Due to this proximity, scientists and engineers can push the boundaries of autonomy while having the ability, in some cases, to service and update systems with astronauts on the surface or in orbit.

Future lunar exploration will leverage a variety of spaceflight capabilities, including advanced orbiters, landers, rovers, small spacecraft, and humans. The following Moon Design Reference Mission (DRM) scenarios illustrate ways in which autonomy can be incorporated to enhance and facilitate exploration to unexplored regions of our nearest neighbor.

Design Reference Mission Scenarios

The goals of the Moon DRM scenarios in this document are to explore new areas of the Moon and collect key new measurements to tie to remote datasets and answer important science questions. These DRM scenarios are not intended to be a comprehensive list of lunar missions, nor should these notional design reference missions be construed as being the only lunar missions that would benefit from leveraging autonomy technologies. Rather, these missions are generic scenarios where autonomy enables science and exploration while also advancing the use of autonomy deeper into the Solar System.

- A **long-duration, high-speed rover** is a surface-exploration mission designed to investigate hundreds of scientific sites over a 1000-km traverse during two Earth years. The goal of the long-duration, high-speed rover mission is to use autonomy to navigate and avoid hazards while it travels across the surface between a set of key waypoints. The rover and payload suite will acquire scientific measurements over a broad area and address many key scientific objectives.

- **Orbital polar resource explorers** would use small distributed systems to survey potential lunar surface volatile deposits from orbit to provide preliminary scouting of resource sites.
- A **sub-lunarean void explorer** would explore a void autonomously without user guidance and assess the utility of the sub-lunarean environments for human habitation and shelter while increasing the understanding of the history of mare volcanism and implications for other terrestrial planets.

Critical Autonomous Technologies

The critical autonomous technologies that will enable all three of these scenarios are **situation and self-awareness, reasoning and acting,** and **collaboration and interaction**, including:

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control
- Goal and task negotiation

Supporting Technologies

The key supporting technologies required to achieve these DRM scenarios include:

- Light detection and ranging (LiDAR) –improve autonomous hazard avoidance
- Stereo imaging and processing –facilitate onboard processing and navigation tasks
- Inertial Measurement Units (IMUs) – advance state estimation and monitoring of operations
- Advanced onboard processing and modeling – enable situational awareness in decision making
- Cross-link communications – advance multi-robot and team exploration to increase return
- Machine-learning platforms/architectures – identify interesting targets of opportunities in bandwidth-limited situations

A summary of findings related to the Moon DRM scenarios is presented in Part IV.

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.

Part II: The Case for the Moon

As described in the 2007 National Research Council's "Scientific Context for the Exploration of the Moon" report (Space Studies Board, 2007) and the 2011 Planetary Decadal Survey "Visions and Voyages" report (National Research Council Committee on the Planetary Science Decadal Survey, 2011), and subsequently restated in the 2018 Lunar Exploration Analysis Group (LEAG) "Advancing Science of the Moon" report (Lunar Exploration Analysis Group, 2018), advances arising from recent lunar missions produced dramatic new questions about lunar volcanism, volatiles, impact processes, lunar tectonics, and the lunar environment.

Furthermore, the Moon is the most accessible target for resuming human exploration beyond low-Earth Orbit, with vast and accessible resources, making it the critical enabling asset for any United States activities beyond low-Earth orbit (Committee on Human Spaceflight, National Research Council, 2014; Lunar Exploration Analysis Group, 2011; P. D. Spudis, 2016; P. Spudis & Lavoie, 2011). The Moon's importance is appropriately reflected in Presidential Space Policy Directive 1, which directs NASA to return United States Astronauts to the lunar surface for long-term exploration and utilization and directs NASA to land United States Astronauts on the lunar surface by 2024 as a prelude to the establishment of a permanent lunar surface facility by 2028.

As explicitly noted by the Advancing Science of the Moon Specific Action Team (ASM-SAT) report, surface exploration of the Moon is required to not only provide ground-truth for key orbital results, but also to make progress in addressing all key science and exploration questions. Goals and objectives for NASA lunar exploration are defined by the NASA Lunar Exploration Analysis Group in the United States Lunar Exploration Roadmap (US-LER), created by LEAG at the request of the NASA Advisory Council and developed through a comprehensive community engagement process that synthesized inputs from scientists, engineers, and policymakers.

Developing automation technologies to use on the Moon is a logical way of enhancing the exploration efforts on the Moon for both human and robotic exploration, with clear benefits for enhancing scientific exploration of the Moon as well as using developing lunar resources commercially. This concept is reflected in the fact that the "Feed Forward" theme of the US-LER explicitly calls for developing autonomy for lunar applications to most effectively prepare for voyages to destinations beyond the Earth-Moon system. Autonomy for lunar exploration is considered desirable in the US-LER for enabling long-duration traverses across the lunar surface while minimizing human or flight controller interaction with the surface mobility systems.

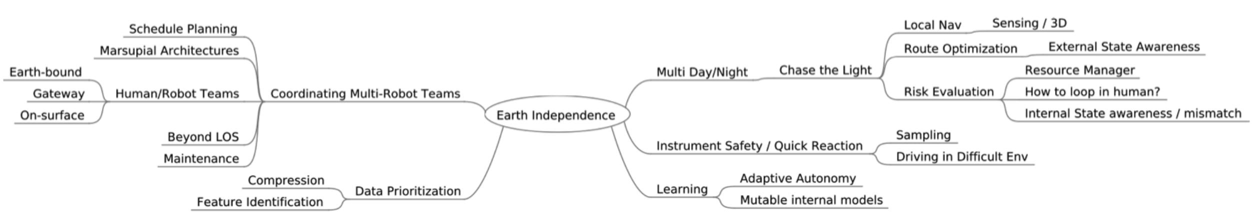

Fig. 1: Motivations for lunar exploration autonomy from workshop breakout discussions

Part III: Design Reference Mission Scenarios

Moon DRM Scenario 1: A Long-duration, High-speed Rover

The goal of the long-duration, high-speed rover mission is to use autonomous mobility to acquire scientific measurements over a broad area and address many key scientific objectives, including:

- Providing ground truth for all terrain types measured by orbiting spacecraft.
- Characterizing the composition of the components of the lunar regolith in order to provide important constraints on the lithologic diversity of the crust.
- Characterizing the lunar surface to investigate volcanic processes and increase our understanding of the evolution of the lunar crust.
- Investigating and quantifying possible magnetic anomalies and lunar-surface swirls.
- Creating a sample cache that could be retrieved by future human and robotic exploration systems.
- Detecting, assaying, and mapping potential resources to identify and quantify vital resource reserves to enable commercial exploitation.
- Quantifying the actual impacts of dust, its environments, and interactions with systems to validate lunar operational best-practices and impact future logistics and supply chains for human inhabitants.
- Measuring the radiation environment (primary and secondary) present on the lunar surface to inform future habitat design.
- Demonstrating applicability of advanced autonomy technologies to exploration of other destinations, such as Europa.

The Concept of Operations:

A long-duration, high-speed rover enables measurement collection and provides ground truth for remotely sensed data products over a wide range of geologic terrains (i.e., mare and highlands). To enable the long traverses, the onboard instrument suite will acquire most of the measurements while in motion or during short pauses. This concept is in stark comparison to the rovers studying Mars, which stop frequently for long periods to gather measurements. While this architecture limits the time for intensive studies of a particular site, the coverage gained by a highly mobile platform will increase the scientific return over a diverse set of geologic materials.

Over a range of over 1000 km, a series of high-priority targets will answer both scientific and exploration questions in a single mission. While there are many traverse options, one traverse example initiates in southern Oceanus Procellarum near the Reiner Gamma Constellation Region of Interest, continues through the Marius Hills volcanic complex, proceeds northward along the youngest mare basalts as defined by crater statistics (Hiesinger et al., 2011), and concludes with an in-depth exploration of the Aristarchus plateau **[Fig. 2]**. This traverse includes diverse lithologies, regions of unexplained albedo and color, magnetic anomalies, a wide range of lunar volcanic types and ages, and includes four Constellation Regions of Interest (Reiner Gamma, Marius Hills, Aristarchus 1 and 2) (Gruener and Joosten, 2009; Jolliff et al., 2010).

After landing on the lunar surface and performing the necessary checkout procedures for the navigation, communication and instrument systems, the rover will begin traversing toward Reiner Gamma and collecting science measurements. Lunar Prospector observations showed that the tadpole-shaped albedo signature (Reiner Gamma) is located on one of the strongest crustal magnetic anomalies (Mitchell et al., 2008). Using an onboard magnetometer, the rover can sample the magnetic field strength in detail to examine the distribution/structure of the crustal magnetic source and its correlation with albedo variations.

After exploring Reiner Gamma, the rover will autonomously navigate toward the Marius Hills region using the Cruise Mode. As the rover approaches the main site, the rover will begin visiting as many different volcanic features as possible to acquire high-resolution images of the diversity of volcanic features present (cones, domes, rilles, craters). Additionally, the rover will image the surrounding regolith to better understand the variations in morphology and flows. Meanwhile, other instruments will map out the mineralogy of basalts across the region as well as examine the elemental abundances in the lava flows.

The rover will then travel to the Aristarchus Plateau. On the way, the rover will traverse over what is thought to be the youngest mare as determined by crater count statistics (Hiesinger et al., 2011). As it reaches the Plateau, the rover will begin to investigate the history of explosive volcanism at the site and begin to address questions about the depth of origin and composition of primary magma, degree of fractional crystallization, constraints on mare petrogenesis, and the composition of lunar interior. The rover will also sample the pyroclastic layer, examine its thickness using exposures created from impact events and evaluate its potential consumption for future in situ resource utilization (ISRU).

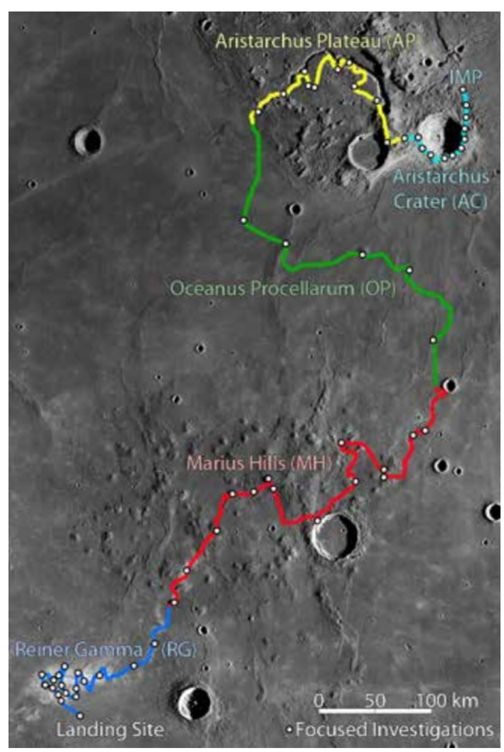

Fig. 2: Example of a long-duration traverse

The traverse on Aristarchus Plateau closely follows the primary rille (Cobra Head), gaining in elevation and making its way to the Aristarchus Crater. Once at Aristarchus Crater, the rover will investigate the surface regolith to better understand the composition, structure, and variability of the crust. The rover will also survey the impact melts along with silicon-rich materials (southwestern rim) and olivine/glassy materials (southeastern rim). The overall goal is for the rover to identify and characterize at least four lithologies in Aristarchus Crater ejecta. Additionally, observations acquired along this traverse will help us better understand the impact history and the modification, redistribution, and mixing associated with impacts of this magnitude.

While this concept includes only a single rover, future missions and campaigns may implement multiple rovers and incorporate human explorers on the surface. These advancements will require communication and coordination between the robotic assets as well as the human explorer.

The Autonomous Capabilities Needed:

1. Autonomous Local Navigation

Autonomous local navigation is enabling for the long-duration, high-speed rover concept. To enable this mobility, the rover will have to collect measurements while in motion with either a LiDAR system or a set of optical stereo cameras. This information will be processed onboard to build a model of the surrounding environment. From the model, potential hazards will be identified, and an optimal traverse path will be computed without interaction with human controllers or computational resources on Earth. Finally, an IMU with the aid of an onboard computer will be needed to assess the current state of the explorer and to monitor the progress to ensure the system stays within the operating limits.

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

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control

2. Adaptive Autonomy

Adaptive autonomy builds on the autonomous navigation outlined above, but enables a human monitor to adjust a traverse or the measurement objectives based on new observations. This technology will enhance the capability and science return and provide a flexible architecture for science exploration.

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

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Event and trend identification
- Anomaly detection
- Execution and control
- Fault diagnosis and prognosis
- Fault response
- Learning and adapting
- Modeling and simulation

Other technologies that are needed to support autonomous and adaptive navigation are high-capacity computing power for onboard processing as well as machine learning platforms/architectures to identify anomalies and characterize the surrounding environment.

3. Multiple Robots/Assets Working in Coordination

As the size of an exploration region increases, multiple robots and assets working in coordination will enable new types of datasets and science. For example, multiple assets strategically spaced can be used together to monitor processes such as the mobility of volatiles in and around permanently shaded regions near the lunar poles. Likewise, an array of long-lived rovers can coordinate traverses and measurement tasks. If a large number of surface assets have a mobility component, it will not be possible to individually control and monitor using the standard operation methods used for Mars rovers. Therefore, the network of assets will need to communicate and coordinate with each other autonomously to identify the objectives of each.

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

- Mission planning and scheduling
- Activity and resource planning and scheduling
- Fault diagnosis and prognosis
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Operational trust building
- Verification and validation

Other technologies that are needed to support this autonomy are cross-link communications, team-level localization, and cooperative power sharing/distribution (wired or beamed power transfer).

4. Planning and Coordination in Multi-Robot and Human-Robot Teams

Future human missions may use mobile robotic assets to help collect measurements and complete maintenance tasks around a lunar outpost. As lunar ISRU technologies are developed and implemented, planning and coordination of multi-robot and human-robot teams will be required. The development of this technology will "feed forward" to NASA goals for sustainable human and robotic exploration of the Solar System.

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

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Mission planning/scheduling
- Activity and resource planning/scheduling
- Fault diagnosis and prognosis
- Fault response
- Learning and adapting
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Operational trust building
- Test and evaluation

Other technologies that are needed to support this autonomy are scheduling/planning in high-dimensional state spaces, with uncertain observations of environment and human performance, team actions, and shared beliefs.

Moon DRM Scenario 2: Orbital Polar Resource Explorers

As noted by the recent LEAG Advancing Science of the Moon Specific Action Team (ASM-SAT) report (LEAG 2018), the past decade has provided a wealth of new data and an abundance of research focused on understanding polar volatiles and the polar environment **[Fig. 3]**. Interest in the special environment of the lunar poles has grown dramatically, but an understanding of polar volatiles and

Fig. 3: The Rim of Shackleton crater, a high-priority destination for future human and robotic exploration.

the fundamental questions about their origin and evolution remain unanswered and will remain so without more mission results, including orbital measurements, in situ analyses, and returned samples. Many of the technologies outlined above for a long-duration surface exploration rover would also be highly applicable to the unique lunar polar environment, where intelligently and autonomously moving in and out of the sunlight is necessary to enable long-duration operations on the surface (Speyerer et al., 2016; Speyerer & Robinson, 2013).

The 2018 Space Resources Roundtable/LEAG Workshop on Lunar Polar Prospecting, along with the 2017 LEAG/ International Space Exploration Coordination Group (ISECG) polar volatile coordination dialog Specific Action Team, also highlighted the value of low-orbiting small spacecraft platforms **[Fig. 4]** at addressing measurement requirements between low-lunar orbital (LLO) and surface measurements (e.g., the notional Artemis-1 co-manifested LunaHMap mission). The Lunar Polar Prospecting Workshop (Morris and Sowers, 2018) suggested that a CubeSat swarm could be employed to gather high-resolution remote sensing data at the lunar poles relevant to the existence and characterization of volatile resources. In this scenario, CubeSats would fly as low as possible (10-20 km above the surface).

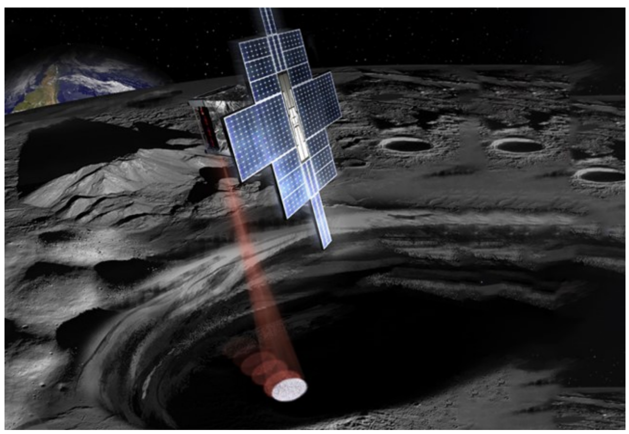

Fig. 4: The Lunar Flashlight mission, illustrated here, highlights the potential value of small spacecraft for lunar resource exploration.

The Concept of Operations:

For this polar volatile explorer, multiple SmallSats would be engaged to fly over the polar regions at low altitudes (10-20 km above the surface). Through a series of coordinated measurements, the satellite array can aggregate their individual measurements which could then be synthesized into a high-resolution dataset covering numerous locations in the polar region to identify potential ice deposits. This same mission could also include the deployment of multiple (even hundreds) low cost impactors to provide needed ground-truth measurements. The impactors could be outfitted with instruments to detect and quantify the volatiles present in the permanently shaded cold trap.

The Autonomous Capabilities Needed:

Autonomous navigation and multi-robot communication /coordination are key capabilities needed to carry out this type of mission.

5. Autonomous Local Navigation

With potentially hundreds of SmallSats needing to coordinate, it is important that each be able to navigate and orientate autonomously and independently of ground-based controllers. This capability will reduce the need for manual commanding and communication during these measurement sequences. Each satellite will need the ability to localize itself relative to the target and other satellites in the network with low-powered IMUs and efficient star trackers. Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control

6. Multiple Robots/Assets Working in Coordination

The science measurements provided by this network of SmallSats are only valid when observations are carried out in coordination with each other. Therefore, the network of assets will need to communicate and coordinate with each other autonomously to identify the objectives and measurement sequences of each.
Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for this capability are:

- Mission planning and scheduling
- Activity and resource planning and scheduling
- Fault diagnosis and prognosis
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Operational trust building
- Verification and validation

Other technologies that are needed to support this autonomy are cross-link communications and team-level localization.

Moon DRM Scenario 3: Sub-lunarean Void Explorer

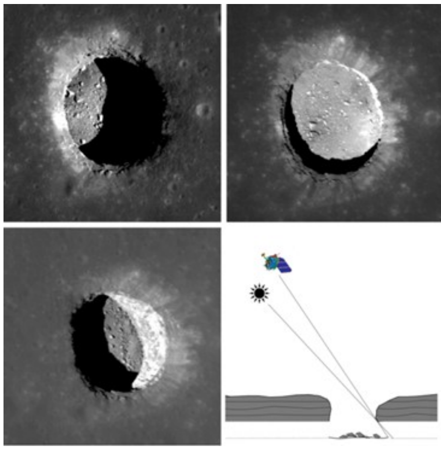

Fig. 5. Sublunarean void under different illumination conditions. **Fig. 6:** Sublunarean void explorer concept.

As outlined by the recent LEAG/Solar System Exploration Research Virtual Institute (SSERVI) Lunar Science for Landed Missions workshop (Jawin et al., 2019), data from the Japan Aerospace Exploration Agency (JAXA) Space Science SELenological and ENgineering Explorer (SELENE) and NASA Lunar Reconnaissance Orbiter (LRO) missions have resulted in discoveries of "skylights" or "pits" in mare basalts **[Fig. 5]** that have been interpreted as breached lava tubes (Haruyama et al., 2009a; Robinson et al., 2012; Wagner and Robinson, 2014), and the walls of these pits provide new information about mare basalt emplacement as a series of thin flows. Such pits provide a site in which a stratigraphic sampling of mare basalt lava flows could occur (along with paleoregolith). Such pits are also interesting destinations for human exploration, since they provide natural radiation shielding and a benign thermal environment. Entering and exploring a pit crater is a unique lunar science objective – the characteristics of these presumed lava tubes, including how far they extend into the subsurface, are presently unknown and further exploration is required. Since uncrewed precursor missions will have to operate outside of Earth line-of-sight while in a sublunarean void, autonomy is uniquely enabling for exploration and required to achieve Decadal objectives. Since the observed floors of the sublunarean voids are rough, other mobility technologies will be required to explore the voids. Both propulsive robotic spacecraft (Robinson et al. 2014) **[Fig. 6]** and advanced mobility systems (e.g., Whitaker, 2014) have been proposed.

The Concept of Operations:

In this design reference mission, a lander will use optical navigation to identify and lock on to the edges of the pit [**Fig. 5**]. As it approaches the pit, it will navigate down the center of the pit and enter at a slow vertical velocity (1 m/s) enabling imaging of the pit walls to better understand the layering present. As it approaches the floor, optical hazard avoidance will be used to avoid large boulders that have eroded off the pit wall and identify a safe landing location. Once landed and the immediate area around the landing site is characterized, a small spherical flying robot (Thangavelautham et al., 2012; Strawser et al., 2014) will be deployed. Lithium hydride and water/hydrogen peroxide will power a series of micro-thrusters that pulse and allow the spherical flying robot to explore the pit region. One of the main science questions is whether these features are just collapsed features or the opening to a large void space or lava tube. Without the ability for direct human control and navigation, the robot will have to determine its location, identify interesting targets, and explore the void space autonomously. This mission may include multiple deployable robots; in such cases, individual measurement tasks and communications will need to be coordinated.

The Autonomous Capabilities Needed:

As with the prior Moon DRM scenarios, local navigation and multiple coordination are needed to enable the mission.

7. Autonomous Local Navigation

These regions have never been explored and satellite observations provide little insight into what can be expected. For this mission to be successful, the lander and individual robots will need to navigate, avoid potential hazards, and relay back their positions without any human interaction.

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

- Sensing and perception
- State estimation and monitoring
- Knowledge and model building
- Hazard assessment
- Mission planning and scheduling
- Activity and resource planning and scheduling
- Motion planning
- Execution and control

8. Multiple Robots/Assets Working in Coordination

This mission architype will enable multiple propulsive robots to explore the lunar pit and potential lava tube. To maximize the science return, the multiple robots should work in coordination to maximize the explored area and relay back the most comprehensive measurements of the pit's features.

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

- Mission planning and scheduling
- Activity and resource planning and scheduling
- Fault diagnosis and prognosis
- Joint knowledge and understanding
- Behavior and intent prediction
- Goal and task negotiation
- Verification and validation

The Relevant Research and Development Projects for these DRM scenarios

- Institutions researching Simultaneous Localization and Mapping (SLAM) and other self-driving technologies (multiple institutions)
- Sensor safety- i.e., avoiding pointing sensor at the Sun (NASA Ames)
- Planning for sensor limitations (Sun in field of view (FOV)/High Backscatter)
- Monitoring and characterization of rover health (e.g., solar availability)
- Sensor technology for detecting hazards
- Multi-robot teams (e.g, robot soccer, Department of Defense swarm projects such as the Defense Advanced Research Projects Agency's OFFensive Swarm-Enabled Tactics [OFFSET])
- Contemporary research in belief space planning and human-robot teaming
- Reduce risk by better characterizing/utilizing system capabilities
- Reduce risk by protecting assets more effectively
- Reduce risk of wasting science resources/mission life

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

The working group identified several challenges that pose risk for all these scenarios and that could be addressed through application of autonomy:

- **Reduce risk by selecting safe traverses: avoiding slope and hazardous surface features when possible**
- **Reduce risk of mission failure due to limited operation time**
- **Reduce risk of mission lifetime reduction using optimized resource allocation strategies**

For all of these risks, we need to leverage contemporary work in natural language/understanding, psychology of human-robot teams, and human state/performance estimation.

However, maximum application of autonomy depends on the mission objectives. Risk reduction could also be achieved leveraging autonomy by enabling missions to visit more locations than a single short-duration rover, or to better reach an objective (i.e., get into a lava tube without communications with Earth), or to accomplish multiple objectives simultaneously. However, this could increase risk because of potential n^2 interactions (and thus increased complexity over single system missions).

Inherently, for this report we assume that multiple robots are too costly to operate from Earth, or that it is more efficient or effective for the robots to work autonomously (rather than with humans in the loop), or these robots have to operate when humans cannot be "in the ops loop" (e.g., no communication link from the Moon to Earth, Gateway, etc.). However, advances in technologies and/or launch vehicles may remove perceived risks and complexities of multiple system "swarm" style missions, as proposed for the Orbital Polar Resource Explorers DRM scenario.

Investments in architecture studies may well be required. There is a tradeoff between distributed/centralized team control, particularly when dissimilar uncrewed systems are operating individual heterogeneous robots or when there are dynamic considerations.

Part IV: Findings

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

1) Establish study teams to investigate the current use of autonomous navigation and hazard avoidance
    a) Leverage recent industry advances in autonomous navigation
    b) Assess current Technology Readiness Levels (TRLs) and identify shortcomings
2) Establish requirements for onboard analysis capabilities for conducting autonomy
    a) Examine the processing requirements to conduct navigation onboard and identify central processing unit (CPU), storage, and power requirements
    b) Study how to leverage the limited downlink opportunities in some mission scenarios
3) Identify hardware that can enable improved autonomy; examples include:
    a) Low-power LiDAR for hazard assessment
    b) Sunlight-tolerant imagers with sunglasses, adaptive polarizers, partial sunshade, etc. to improve the dynamic range in extreme lighting environments
    c) Low power and accurate IMUs for situational awareness

The investment in autonomous navigation not only has the ability to enhance and enable a long-lived rover as the one discussed in this report, but can also feed into the design of other missions that incorporate mobility. By identifying hazards and optimal traverse paths, the asset can overcome obstacles and not wait for human interaction. As we explore further into the solar system, the communication time increases and human involvement can substantially hamper progress, and in some extreme environments, the wait can even put the mission at risk. Additionally, the inclusion of autonomy in almost any form will increase the processing requirements of the onboard computer. It is essential that NASA test and develop new processors that can handle the increased load. This development should be carried out at various scales so that capable processors will be available for power-limited environments such as those encountered on small spacecraft as well as in more resource-rich environments.

Part V: Moon Design Reference Mission Team

The Moon Design Reference Mission team is comprised of:

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Part VI: References

Documents cited:

Committee on Human Spaceflight, National Research Council. (2014). *Pathways to Exploration: Rationales and Approaches for a U. S. Program of Human Space Exploration*. Washington, D. C.: National Academy Press.

Gruener, J. E., & Joosten, B. K. (2009). NASA Constellation Program Office Regions of Interest on the Moon: A Representative Basis for Scientific Exploration, Resource Potential, and Mission Operations. *LPI Contributions*, *1483*, 50–51.

Haruyama, J., Hioki, K., Shirao, M., Morota, T., Hiesinger, H., van der Bogert, C., Miyamoto, H., Iwasaki, A., Yokota, Y., Ohtake, M., Matsunaga, T., Hara, S., Nakanotani, S., Pieters, C. M. (2009), Possible lunar lava tube skylight observed by SELENE cameras, *Geophys. Res. Lett.*, 36, L21206, doi:10.1029/2009GL040635.

Hiesinger, H., Head, J. W., Wolf, U., Jaumann, R., & Neukum, G. (2011). Ages and stratigraphy of lunar mare basalts: A synthesis. *Geological Society of America Special Papers*, *477*, 1–51. https://doi.org/10.1130/2011.2477(01)

Jawin, E. R., Valencia, S. N., Watkins, R. N., Crowell, J. M., Neal, C. R., & Schmidt, G. (2019). Lunar Science for Landed Missions Workshop Findings Report. Earth and Space Science, 6(1), 2–40. https://doi.org/10.1029/2018EA000490

Jolliff, B. L., Wiseman, S. A., Lawrence, S. J., Tran, T. N., and the LROC Science Team. (2010) Scientific return from systematic imaging of the constellation exploration sites: Compton-Belkovich example. Lunar and Planetary Science Conference, #2412.

Lunar Exploration Analysis Group. (2011). The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities. Retrieved from http://www.lpi.usra.edu/leag/LER-Version-1-1.pdf

Lunar Exploration Analysis Group. (2018). *Advancing Science on the Moon* (LEAG Specific Action Team Report) (p. 69). Houston, TX: LEAG. Retrieved from https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

Mitchell, D. L., Halekas, J. S., Lin, R. P., Frey, S., Hood, L. L., Acuña, M. H., & Binder, A. (2008). Global mapping of lunar crustal magnetic fields by Lunar Prospector. *Icarus*, *194*(2), 401–409. https://doi.org/10.1016/j.icarus.2007.10.027

Morris, G., & Sowers, G. (2018). *Lunar Polar Prospecting Workshop: Report*. Space Resources Roundtable. Retrieved from https://isruinfo.com/public//docs/LPP_2018_final_report.pdf

National Research Council Committee on the Planetary Science Decadal Survey. (2011). *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, D.C.: The National Academies Press. Retrieved from http://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022

Robinson, M., Ashley, J. W., Boyd, A. K., Wagner, R. V., Speyerer, E. J., Ray Hawke, B., ... Van Der Bogert, C. H. (2012). Confirmation of sublunarean voids and thin layering in mare deposits. *Planetary and Space Science*, *69*(1), 18-27. https://doi.org/10.1016/j.pss.2012.05.008

Robinson, M. S., Thanga, J., Wagner, R. V., & Hernandez, V. A. (2014). Arne — Sublunarean Explorer (Vol. 1820, p. 3025). Presented at the Annual Meeting of the Lunar Exploration Analysis Group. Retrieved from http://adsabs.harvard.edu/abs/2014LPICo1820.3025R

Space Studies Board, N. R. C. (2007). *The Scientific Context for Exploration of the Moon: Final Report*. Washington, D. C.: National Academy Press. Retrieved from http://www.nap.edu/catalog/11954/the-scientific-context-for-exploration-of-the-moon-final-report

Speyerer, E. J., Lawrence, S. J., Stopar, J. D., Gläser, P., Robinson, M. S., & Jolliff, B. L. (2016). Optimized traverse planning for future polar prospectors based on lunar topography. *Icarus*. https://doi.org/10.1016/j.icarus.2016.03.011

Speyerer, Emerson J., & Robinson, M. S. (2013). Persistently illuminated regions at the lunar poles: Ideal sites for future exploration. *Icarus*, *222*(1), 122–136. https://doi.org/10.1016/j.icarus.2012.10.010

Spudis, P., & Lavoie, A. (2011). Using the resources of the Moon to create a permanent, cislunar space fairing system. In *AIAA SPACE 2011 Conference & Exposition* (p. 24). Long Beach, CA: American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2011-7185

Spudis, P. D. (2016). *The Value of the Moon: How to Explore, Live, and Prosper in Space Using the Moon's Resources*. Washington, DC: Smithsonian Books.

Strawser, D., Thangavelautham, J., Dubowsky, D. (2014) A passive lithium hydride based hydrogen generator for low power fuel cells for long-duration sensor networks. *International Journal of Hydrogen Energy*, 39, p. 10216-10229.

Thangavelautham, J., Strawser, D., Cheung, M., Dubowsky, D., (2012) Lithium hydride powered PEM fuel cells for long-duration small mobile robotic missions. *IEEE International Conference on Robotics and Automation (ICRA).*

Wagner, R. V. & Robinson, M., (2014) Distribution, formation mechanisms, and significance of lunar pits. Icarus. 237, p. 52-60.

Whittaker, R. W. (2014). *Exploration of Planetary Skylights and Tunnels*. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20190001167

The Ocean Worlds Design Reference Mission Report

Part I: Executive Summary

One of the most profound discoveries in planetary exploration is the evidence for large quantities of liquid water on several bodies in our Solar System, aptly named "Ocean Worlds." In an effort to extrapolate our understanding of life on Earth to the cosmos, "go to the water" has become the guiding principle in our search for evidence of extraterrestrial life. Thus, Ocean Worlds have become key astrobiology targets, and many outstanding questions can only be answered through direct contact with their subsurface liquid water.

The challenges involved in implementing robotic subsurface missions on Ocean Worlds are immense, and advanced autonomy may be among the most demanding technology developments that will be required. The current state of practice for autonomous operations of Mars rovers and distant spacecraft is highly *robust*, *deliberative*, and *protective*; that is, the system makes a plan that is "safe" with respect to known uncertainties and promptly triggers a "safe mode" in the event of any anomalies. Ocean Worlds, however, present an environment that is far more uncertain, dynamic, and communication-constrained, which will require autonomy that is *adaptive*, *reactive*, and *resilient*. For example, the dynamic nature of plume ejecta on Enceladus or the harsh radiation of Europa prohibit human-in-the-loop control, especially during long-duration communication blackouts such as the two-week period during solar conjunction. Ocean World probes must be equipped with the ability to *learn* from their interactions with the environment, *react* to imminent hazards, and *make real-time decisions* to respond to anomalies.

The goal of this Design Reference Mission (DRM) is to survey the key autonomy technologies that will *enable* robotic subsurface missions to Ocean Worlds, identify technology gaps that warrant further research and development, and recommend next steps. Though mission concepts for subsurface ocean access are broad and in an early stage of development, we focus our attention on two specific architectures that represent the exploration approaches: a “cryobot” probe for penetration of Europa’s or Enceladus’ ice crust, and a “crevasse explorer” for the surface entry and descent into active vents on the south pole of Enceladus or potential crevasses on Europa. These DRM scenarios constitute a subset of all possible architectures, however, we attempt to address them in a general way that highlights key autonomy requirements across a broad range of Ocean World missions. In short, we find that, while there are technology gaps in almost all domains of autonomy, a few categories stand out as high priority for development in the case of both DRM scenarios: (1) Knowledge and Model Building, (2) Hazard Assessment, (3) Execution and Control, (4) Verification and Validation, and (5) Autonomous Science.

The systems needed to accomplish the goals of this DRM require a long runway to succeed. A key driver is time and critical mass of work to develop the technology to a point of maturity that reduces the risk for mission implementation. The development must be ‘requirements-driven and managed,’ rather than a ‘best effort tech-push’ approach. The DRM team finds that the following key steps need to begin to propel successful development.

Develop quantified requirements for the Ocean Worlds Design Reference Mission with clearly defined metrics for autonomy system maturation

- The ocean worlds environment should be defined with fidelity necessary to define environmental requirements for the autonomy technology at the system capability level and at the component level, as defined in Part III and Part IV, respectively. This allows for measurement of technology maturity directly in the context of the DRM.
- A product breakdown structure of the complete autonomy system is needed to organize and support maturation of the technology. This structure is a comprehensive, hierarchical structure of deliverables — physical and functional — that make up the autonomy system.

Specify a software simulation and hardware validation and verification (V&V) environment that the national community will ultimately build and use to assess autonomy systems

- Build an ocean worlds software system simulation environment that can simulate the performance of autonomy subsystems and components. Build high-fidelity models of the subsystems and components that will be simulated in the larger system simulation environment.
- Build hardware testbeds to experimentally test autonomy subsystems and components.

- Construct a community V&V certification framework that will assess proposed autonomy systems against the quantified metrics developed above.

Build system and component technologies as described in Section IV. The developments will utilize the defined DRM environments, product breakdown structures, and V&V environments described above.

Part II: The Case for Ocean Worlds

The NASA Outer Planets Assessment Group (OPAG) Roadmaps to Ocean Worlds (ROW) group has outlined the scientific content and priorities for investigations that are needed for the exploration of ocean worlds[5]. They begin by stating:

"The overarching goal of an Ocean Worlds exploration program as defined by ROW is to 'identify ocean worlds, characterize their oceans, evaluate their habitability, search for life, and ultimately understand any life we find.' ... There are several—if not many—ocean worlds or potential ocean worlds in our Solar System, all targets for future NASA missions in the quest for understanding the distribution of life in the Solar System."

These worlds beckon with ingredients that potentially harbor extant life. Beginning with the Galileo and Cassini missions, measurements have revealed the presence of global oceans under the icy crust of several moons of Jupiter and Saturn. Other such worlds have been recognized and are being examined by additional missions. Among the moons of Jupiter and Saturn, Europa and Enceladus have their ocean in contact with the rocky core, providing an environment similar to the conditions existing on the terrestrial sea-floor where life has developed at hydrothermal vents[6].

[5] Hendrix, Amanda R., T. A. Hurford, and ROW Team. *Roadmaps to Ocean Worlds*. Planetary Science Vision 2050 Workshop #8171. 2017.
[6] Hand, K. P., et al. *Report of the Europa Lander Science Definition Team*. [https://europa.nasa.gov/system/downloadable_items/50_Europa_Lander_SDT_Report_2016.pdf] Posted February 2017.

The National Research Council (NRC) reports[7, 8] and NASA Advisory Groups[9, 10] have placed a high priority on the science exploration of our solar system's Ocean Worlds, such as Europa and Enceladus. Three major themes are a focus[11]:

- Geodynamics: What is the structure and dynamic state of the icy crust and ocean interface?
- Habitability: Does the Ocean World's past or present state provide the necessary environments to support life?
- Life Detection: Did life emerge on one of these Ocean Worlds, and does it persist today?

In order to pursue answers to the questions in these themes, new and unique robotic system capabilities will be necessary. Accessing the oceans presents considerable difficulty due to a number of issues including the depth and composition of the icy crust, the time needed to travel through the crust or crevasse, the power needed to propel a probe, communication of scientific and engineering data though the ice and back to Earth, entry and mobility in the ocean, and autonomous operations for the life of the mission. To quantify and outline capabilities for ocean worlds autonomous systems, two concepts for the design reference mission are defined – a Cryobot concept that would travel through the icy crust to the expected ocean below, and a Crevasse Explorer that would be mobile on the surface of the body and descend into a crevasse. These concepts are meant to be an abstraction of the autonomy capabilities for vehicles that can travel 'through-the-ice' or 'into the crevasses' and can apply to general ice environments. The autonomy capabilities can directly trace to the currently known environments and system objectives for the exploration of Europa and Enceladus; they would also trace to the surface and subsurface of Titan; it is expected that they would also trace to additional ocean worlds that, as they become better understood, have characteristics similar to those of these bodies.

The exploration vehicles will be required to operate in an environment that is not characterized with enough fidelity to create scripted a priori operational scenarios, or teleoperate with humans in-the-loop. The environment may be dynamic, as in crevasse-plumes, or require adaptable operations, as in vehicle movement through the ice, and obstructions must be sensed and avoided. It is assumed that the environment cannot be characterized with enough fidelity, even from prior remote sensing missions, to allow unattended operations and the

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[7] Space Studies Board, National Research Council. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press. 2012.

[8] Committee on the Astrobiology Science Strategy for the Search for Life in the Universe, Space Studies Board, National Research Council. *Astrobiology Science Strategy for the Search for Life in the Universe.* doi:10.17226/25252. The National Academies Press. [http://nap.edu/25252] 2018.

[9] Hendrix, Amanda R., et al. *Roadmaps to Ocean Worlds*.

[10] Outer Planets Assessment Group Steering Committee. *OPAG Priority Science Questions: Letter to Dr. Lori Glaze, NASA PSD Director*. [https://www.lpi.usra.edu/opag/meetings/aug2019/OPAG-ScienceLetter-to-Glaze_27Aug19.pdf] August 27, 2017.

[11] Hand, K. P., et al. *Report of the Europa Lander Science Definition Team*.

ability to 'pull-over to the shoulder' and wait for direction. The in situ operation on and in the crust of ocean worlds therefore requires a unique level of autonomy to *enable* exploration and meet the goals as described above.

Part III: Design Reference Mission Scenarios

Two concepts are considered to organize the Ocean Worlds Design Reference Mission. They will be outlined separately – in some detail – before collapsing the driving autonomy capabilities needed into one set. The key differences between the two concepts will be identified.

Cryobot Concept

To answer the questions within the scientific themes, one robotic capability is a Cryobot capable of rapid penetration and scientific sampling of thick ice shells down to the ice-ocean interface, where it would deliver an autonomous undersea explorer. Past and current efforts aimed at identifying mission architectures, key concepts of operations, and technologies trades for accelerating the landing and deployment of a Cryobot have highlighted the need for a high level of autonomy throughout many of the mission phases, as described below.

Concept of Operations of the Cryobot Concept

The representative concept of operations is shown in Figure 1. The Cryobot mission concept of operations consists of:

A. **Descent and landing** onto a safe and scientifically interesting region of the surface.
B. **Commissioning and deployment** of the Cryobot to the icy surface.
C. **Initial cryogenic ice entry** phase that requires handling sublimation at the vacuum-ice interface with potentially dry, brittle, particulate-filled material.
D. **Descent** phase through cryogenic ice that slowly warms with depth to near freezing point.
E. **Detection of the ocean-ice interface** followed by safe probe anchoring at that interface.
F. **Ocean exploration:** Deployment of an ocean explorer payload and operations within the water near the interface.

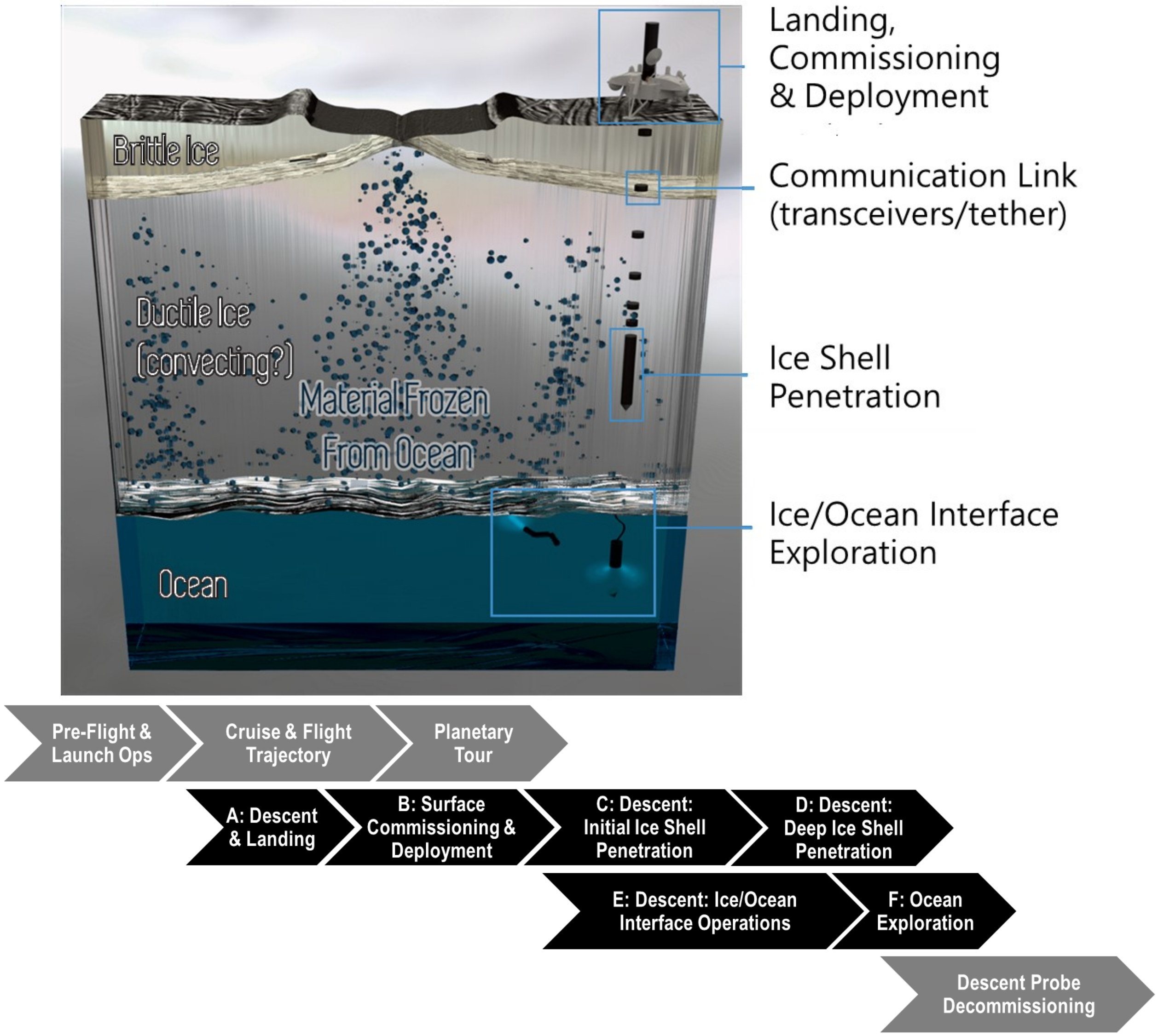

Figure 1. Mission illustration and Concept of Operations for a Cryobot and its ocean-exploring payload.

Autonomy Capabilities needed for the Cryobot Concept

For the full set of operational phases, a set of autonomous mission capabilities are defined. They are shown in Table 1. The mission capabilities are described through a set of high-level objectives that will guide the autonomous development of subsystems for each capability. The assessed level of autonomy needed is described to the right of each capability. Following this assessment, the capability is mapped to the Concept of Operation (CONOPS) phase that would require it. Some capabilities map to one or more concept of operation phases. Within each high-level autonomous capability are several component capabilities (also listed in Table 1) as well as the primary NASA Autonomous Systems Capability Leadership Team (AS-CLT) taxonomy class(es) attributed to each.

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.

Table 1. Autonomous technology mapping for the Cryobot: Mission capabilities, level of autonomy, mapping to CONOPS, component capabilities, and primary AS-CLT taxonomy class for each.

Autonomous Mission Capability	Description and Objectives	Level of Autonomy	Mapping to CONOPS						Component Capabilities	Primary CLT taxonomy class(es)
			A	B	C	D	E	F		
Decelerate, descent, and landing (DDL)	Land within "safe" target region defined from orbital imagery. Redirect as map is refined to maximize landing safety, ice penetration feasibility, and science potential.	High							Terrain relative navigation Real-time hazard detection and avoidance Real-time 3D surface mapping Real-time optimal landing site selection	1.2 1.4, 2.3 1.3 2.1
Ground reconfiguration	Safely transition from landed configuration to communication-ready configuration.	High							Initial checkout: life-support management and control Execute deployables to orient Cryobot and HGA	2.5 2.4
Cryobot deployment	Ensure safe entry of Cryobot into surface within a few weeks after landing to limit radiation dose. Update model of environment for effective control.	Medium							System health management Assess surface properties and penetration performance Control Cryobot insertion	1.2, 2.2 1.3 2.4
Deposit electronics below surface	Ensure all radiation-sensitive electronics are safely deployed below surface behind the Cryobot.	Medium							Detect hole closure and Cryobot state deployment of tethered surface electronics behind	1.2 2.2, 2.4
Automated science	Perform science measurements during descent. For example, some measurements include: imaging, temperature, pressure, grain size, porosity, pH, Ion concentrations, and turbidity.	High							Estimate Cryobot depth Trigger measurements at regular intervals Detect interesting or anomalous measurements Detect and image dynamic events	1.2 2.2 1.6, 2.5 1.6
Hazard avoidance	Detect and avoid potential hazards during descent.	High							Reconstruct hazard map of the anterior subsurface from Plan a 3D path with complex constraints Estimate risk in real time and trigger safe mode for Control Cryobot by steering and varying penetration Estimate and control Cryobot pose to track trajectory	1.3 2.3 1.4, 1.6 2.4 2.4
Deployment of Communication link	Ensure successful deployment of ice transceiver communication pucks and/or tether.	Medium							Estimate Cryobot depth and bandwidth to previous puck Control puck deployment (position and orientation)	1.2 2.4
Cryobot mobility management	Control heat, waterjet, and drill to achieve descent rate and steering. Monitor and mitigate debris build-up.	High							Control fluid heat pumps, drill, and water jet for desired Estimate and mitigate debris build-up Cryobot pose estimation	2.4 1.4, 2.2 1.2
Ice/ocean interface behavior	Stop at ice-ocean interface and do ocean science.	High							Detect ice-ocean interface ahead of Cryobot Detect interface penetration Enact "anchoring" strategy Characterize interface environment	1.3 1.3 2.2, 2.4 1.3
System health and resource management	Manage overall system health and resource allocations.	High							Prioritize data products and manage queue Manage power resources Active thermal management	2.2 2.2 2.4

									Estimate health of communication link to surface Detect and respond to faults	1.2 2.5, 2.6
In-Ocean Exploration	Operate hydrobot with science instruments in the sub-surface ocean tethered from the Cryobot anchored in the ice.	High							Relative pose estimation of hydrobot w.r.t Cryobot buoyancy control for regulating proximity to ice ceiling measure time-varying ocean currents Sample environment at multiple locations with science	1.2 2.4 1.5 2.1, 2.2

A Crevasse Explorer Concept

A second Ocean Worlds exploration concept focuses on crevasses that have been observed to emit plume material, 'bringing the ocean to the surface.' The Cassini mission shows data on a number of Enceladus crevasses including the Tiger Stripes. The active plumes originating from these crevasses suggest an open conduit to a liquid body. Other Ocean Worlds may potentially have similar crevasses. Exploring crevasses and the nearby surfaces creates many challenges including resisting plume forces, dealing with the phase change of water, water vapor occluded imaging, constrained dynamic environments, liquid mobility, and others. The operations and scientific discovery will require deep autonomous capabilities to work in this environment.

Concept of Operations of the Crevasse Explorer Concept

The design reference concept of operations is shown in Figure 2. The crevasse mission concept of operations consists of:

A. **Direct descent and Landing** with pinpoint guidance to one of the largest mass flux vent plumes.
B. **Deployment** of the crevasse explorer.
C. **Surface traverse** to the vent opening.
D. **Transition into Crevasse** requiring bracing or anchoring to react plume forces (this includes science sensing).
E. **Descent** against plume forces through open conduit warmed by active plume (including possible plume chock point traversal).
F. **Transitions into Liquid** including detection and reaching the liquid interface.
G. **Ocean Traversal** and operations within the water.
H. **Science sensing** at the ice-water interface.

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ITEM	Mission Level
A	DDL
B	Deployment
C	Surface Traverse
D	Transition Into Crevasse
E	Descent
F	Transition Into Liquid
G	Ocean Traversal
H	Science Sensing

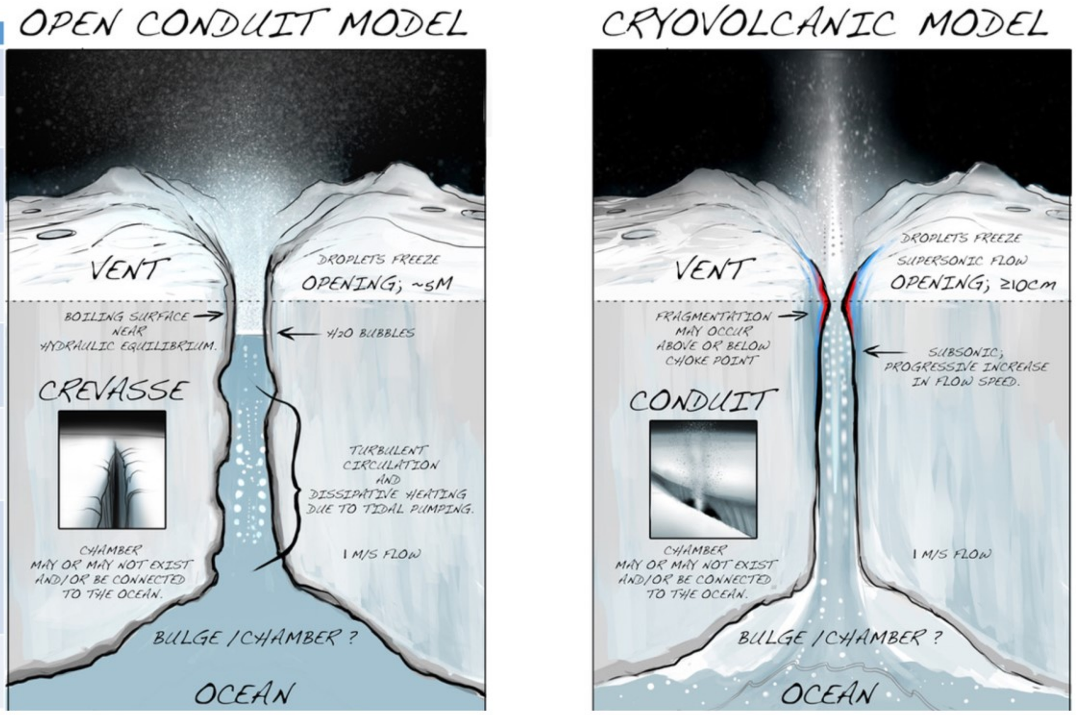

Figure 2. Crevasse Explorer CONOPS Phases

Autonomous Mission Capabilities needed for the Crevasse Explorer Concept

Table 2 shows a mapping of the Autonomous Mission capabilities to the CONOPS of the mission concept.

Table 2. Autonomous technology mapping for the Crevasse Explorer: Mission capabilities, level of autonomy, mapping to CONOPS, component capabilities, and primary AS-CLT taxonomy class for each.

Autonomous Capability	Description / Requirements	Level of Autonomy	Mapping to CONOPS								Component Capabilities	Primary CLT taxonomy class(es)
			A	B	C	D	E	F	G	H		
Decelerate, descent, and landing (DDL)	Landing within ~XXm from target.	High									Terrain relative navigation	1.2
											Real-time hazard detection and avoidance	1.4, 2.3
											Real-time vent characterization and target selection	2.1
Descent module deployment	Safely deploy the descent module from lander and anchor to the surface under 0.01g	Medium									System health management	2.5
											Release and verify deployment	2.4
Power/ Communication management	Manage power and communication health.	High									Prioritize data products and manage queue	2.2
											Manage power resources	2.2
											Active thermal management	2.4
											Estimate health of communication link to surface	1.2
Surface Traversal	Traversal from lander to vent opening.	Medium									Handle environmental state	2.3
											Traversability analysis	1.2
											Localization	1.1, 1.2
											Path/motion planning	2.3
Hazard avoidance	Detect hazards and plan a path to avoid them; make XX m progress over YY hours.	High									3d Perception/motion planning	1.3
											Plan a 3D path with complex constraints	2.3
											Sense anomalous events, adapt to mitigate effects	1.4, 1.6
Situation awareness	Estimate the environmental states (e.g., flow speed/direction, crevasse opening/closing).	High									Onboard model-based inference with multiple sensory inputs	1.2, 1.3, 1.5
Surface/crevasse transition	Detect approaching transition and ensure ability to react to plume forces prior to entering the flow.	High									Plume detection	1.3
											Implement anchoring strategy	2.1, 2.4
											Characterize transition environment	1.3
											Plan initial mobility strategy	2.3
Automated science	Perform target selection, data & sample collection, and analysis partially or fully autonomously.	High									Automated science target detection	1.6, 2.5
											Automated in-situ observation	1.6

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Autonomous Capability	Description / Requirements	Level of Autonomy	Mapping to CONOPS	Component Capabilities	Primary CLT taxonomy class(es)
				Automated sampling	1.3, 2.1, 2.2, 2.4
				Onboard analysis, data triage	1.3
FDIR	Fault detection, isolation, and recovery.	High		Fault detection (Diagnosis)	2.5
				Fault isolation	2.6
				Recovery	2.6
Activity planning & scheduling	Plan & schedule engineering/science activities given high-level goals.	High		Onboard planning & scheduling	2.1, 2.2
Ice/ocean Interface Behavior	At ocean interface, anchor the descent module and asses ocean currents.	High		Detect liquid/ice interface	1.3
				Characterize transition environment	1.3
In-Ocean Exploration	Operate EELS with science instruments in the sub-surface ocean.	High		Relative pose estimation	1.2
				buoyancy control for regulating proximity to ice ceiling	2.4
				measure time-varying ocean currents	1.5
				Liquid mobility operation	1.2

Part IV: A Common set of Autonomy Component Capabilities

While nearly all areas of the Autonomous Systems - CLT taxonomy will be important to the successful execution of an Ocean Worlds mission, the following autonomous system CLT areas are highest priority for the two mission concepts described above.

1.3 Knowledge and model building

The surface, vent, and subsurface environments of ocean worlds will present significant operational uncertainty, which must be resolved and modeled autonomously. Local-scale models are needed to inform reactive controllers and ensure operational safety, while "global" models are needed to anticipate (and plan for) critical transition points (e.g., entering the plume stream or the ice-ocean interface). Key technology capabilities for each DRM are outlined below.

Cryobot:

- Monitoring and modeling of ice penetration performance (e.g., descent rate, steerability, etc.)
- Fore-field mapping and hazard detection via acoustic, RF, and/or optical sensors
- The anticipatory detection of and reaction to the ice-ocean interface

Crevasse Explorer:

- Proprioceptive sensing of surface contact properties
- Modeling the flow field using multiple sensors (e.g., pitot tubes and pressure sensors), as well as the flow-induced forces on the robot
- Mapping the 3D geometry of the crevasse and estimating the robot's location within it
- The anticipatory detection of and reaction to operational transition points, including the plume stream, flow choke points, bulge chambers, boiling interface surfaces, and the ice-ocean interface

*Note that Knowledge and model building heavily leans on CLTs 1.1 – "Sensing and Perception" and 1.2 – "State Estimation and Monitoring," particularly regarding robot localization.

1.4 Hazard Assessment

For novel robotic mobility systems, strategies for the modeling, assessment, detection, and avoidance of potential hazards remain a key technology gap for both the Cryobot and Crevasse Explorer. Key capabilities particularly related to *autonomy* for each DRM are highlighted in *italics* in the table below.

	Cryobot	Crevasse Explorer
Hazard model - Characterization of "performance hazards" that negatively impact operations and critical hazards that pose mission-ending risks.	*Characterize penetration performance (e.g., speed) over a wide range of ice conditions, and define ice "impurities" that must be avoided, such as salt deposits, rocks, and voids.*	*Characterization of surface hazards (e.g., steep slopes) that impede traverse and entry into crevasse, and the conditions under which the upward dynamic pressure on the robot prevents descent.*
Hazard assessment – An a priori assessment and uncertainty quantification of potential hazards in the environment.	Quantify the range of possible subsurface ice conditions based on various geologic models. (See CLT 4.1, V&V)	Quantify the range of possible vent conditions such as the geometry, surface, and flow properties. (See CLT 4.1, V&V)
Hazard detection – The ability for the robot to detect potential hazards with sufficient resolution and range to allow for avoidance or mitigation maneuvers.	Create a fore-field map of potential hazards from acoustic, RF, and optical sensing data at sufficient resolution to allow for avoidance maneuvers.	*Real-time 3D surface mapping and flow estimation.*
Hazard avoidance – Actions the robot can take to avoid or mitigate hazards.	*Risk-aware decision-making and motion-planning algorithms for subsurface guidance given a probabilistic hazard map.*	*Motion-planning algorithms to avoid hazardous terrain during surface traversal and "aerodynamic" maneuvers to mitigate plume back-pressure.*

*Note that Hazard *avoidance* has significant overlap with CLT 2.3 – "Motion Planning," and Hazard *detection* has significant overlap with CLT 1.1 – "Sensing and Perception."

2.4 Execution and control

The Cryobot and Crevasse Explorer constitute novel mobility systems which must reliably operate for long periods of time and beyond the horizon visible to ground control. Thus, actuation and control for interacting with their environment as well as regulating internal health remain key technology gaps for both systems. Key technology capabilities for each are outlined below.

Cryobot:

(1) *Ice Penetration*: Drilling, water jetting, and thermal redistribution will be required for penetration through various types of ice as well as a method for differential melting to enable steering.

(2) *Deployables*: The Cryobot will need to deploy a surface electronics package several meters below the surface, continuously deploy a communications tether and/or periodically deploy communication transceivers ("pucks"), and finally, deploy an ocean exploration module. Deployable anchors may also be required to slow or, at the ice-ocean interface, stop the Cryobot.

(3) *Thermal Control*: active control of a working fluid will be required to redistribute several kilowatts of thermal power from an RTG heat source around the Cryobot for effective ice penetration as well as maintaining safe working temperatures for all critical subsystems.

Crevasse Explorer:

(1) *Mobility*: Novel control strategies will be required to negotiate a wide variety of terrain types during the approach to and descent through a vent, such as anchoring with scalable

reaction forces, handling uneven surfaces, conforming to the internal shape of the vent, and potentially variable buoyancy for ocean exploration.

(2) *Power and communications management* requires an onboard power solution with a repeating communicator solution or a tether. A combination of these features may also be feasible.

*4.1 **Verification and validation***

System level V&V approaches for Cryobot and Crevasse Explorer autonomy will require significant development on three primary fronts: (1) Uncertainty quantification, (2) physical test beds, and (3) software (simulation) test beds.

<table>
<tr><th></th><th>Cryobot</th><th>Crevasse Explorer</th></tr>
<tr><td rowspan="2">Uncertainty quantification</td><td>There is currently little consensus in the scientific community regarding models of the Europan subsurface.</td><td>There are currently competing models in the scientific community regarding the geometry and flow physics of the vents on Enceladus.</td></tr>
<tr><td colspan="2">Rigorous and quantitative studies will be required to define the uncertainty bounds and performance requirements for autonomous operations.</td></tr>
<tr><td>Physical test beds</td><td>Earth analog tests in large-scale ice sheets will help to validate some autonomous Guidance, Navigation and Control (GN&C) subsystems. A large cryogenic hypobaric chamber will also be required to assess penetration performance in more realistic “Europan” conditions.</td><td>A variety of Earth analog sites may capture a range of potential crevasse terrain geometries for testing some autonomous GN&C subsystems. A laboratory test bed will also be required to emulate the high-velocity plume flow and reduced gravity.</td></tr>
<tr><td>Software test beds</td><td colspan="2">A comprehensive, physics-based simulation environment will be required to validate autonomous components as well as the full, integrated autonomy system.</td></tr>
</table>

*Note that V&V has significant overlap with CLTs 4.2 – “Test and Evaluation,” and 4.4 – “Modeling and Simulation.”

Autonomous science:

Due to the multi-hour communication latency to Europa and Enceladus and the dynamic nature of the environments (e.g., due to the inability to stop for the Cryobot and the time-varying nature of plume ejecta for the Crevasse Explorer), autonomy will be required to perform opportunistic science measurements (e.g., in response to anomalous events or local features that are deemed “interesting”) in addition to regularly scheduled measurements. Also, extremely limited data rates will demand a large degree of autonomous data interpretation, compression, and downlink prioritization.

Part V: Potential Challenges, Risks and Needed Supported Technologies

Three key technologies and challenges have been identified to accomplish the technology development defined above.

1. **System capability that integrates component capabilities including a verification and validation system.**

Nearly all of the AS-CLT building blocks will be essential to a successful Ocean Worlds mission. However, they cannot be considered isolated components. A key investment is in integrated system capability, where the AS-CLT building blocks highlighted above are the key tall poles to be validated in an integrated system. For example, a mobility system, while very different for a Cryobot and Crevasse Explorer, requires integration of knowledge and model building, state estimation and monitoring, hazard assessment, execution and control, and motion planning. Key system-level capabilities include mobility, health management, and autonomous science. These system-level capabilities must be verified and validated to achieve the mission goals for unknown situations including dynamic environments and evolving, potentially degrading internal systems.

2. **Building system adaptability to the environment as well as being reactive to the environment, where the environment is dynamic and not well prescribed.**

While the autonomy for the Cryobot/Crevasse Explorer must consist of a diverse set of capabilities as described in Section IV, we found there are a few notable common denominators. First, it has to be not only robust but also *adaptive*. The significant environmental uncertainty will likely prohibit us from finding a fixed design of autonomous behaviors that robustly work for any imaginable situations; rather, it has to adapt its behaviors by continuously learning about the new environment. Second, it has to be *reactive* rather than deliberative. Unlike Mars rovers, visibility is highly limited, environment is dynamic, and orbital reconnaissance is unavailable. Therefore, it has to quickly react to observed situations instead of making a long-range plan deliberatively. Third and finally, it has to be *resilient* rather than protective. Encountering anomalous situations will be likely unavoidable however cautious it is; rather, it has to be designed such that it keeps making progress resiliently even while experiencing anomalies.

3. **Taking advantage of technologies being developed external to NASA.**

A wide range of technologies are being developed external to NASA for industries that are not specifically space-related. These entities have resources much larger than NASA can commit in this area. Some of these technologies have strong overlap with the NASA Ocean Worlds systems and have convincing synergies, if not direct use. One such area is in verification and validation of autonomous systems that are used to certify self-driving cars. Finding approaches that will increase such synergies is essential for success.

Part VI: Findings

The systems needed to accomplish the goals of this DRM require a long runway to succeed. A key driver is time and critical mass of work to develop the technology to a point of maturity that reduces the risk for mission implementation. The development must be requirements driven and managed, rather than a 'best effort tech-push' approach. The DRM team finds that the following key steps need to begin to propel successful development.

Develop quantified requirements for the Ocean Worlds Design Reference Mission with clearly defined metrics for autonomy system maturation

- The ocean worlds environment should be defined with fidelity necessary to define environmental requirements for the autonomy technology at the system capability level and at the component level, as defined in Part III and Part IV, respectively. This allows for measurement of technology maturity directly in the context of the DRM.
- A product breakdown structure of the complete autonomy system is needed to organize and support maturation of the technology. This structure is a comprehensive, hierarchical structure of deliverables — physical and functional — that make up the autonomy system.

Specify a software simulation and hardware validation and verification (V&V) environment that the national community will ultimately build and use to assess autonomy systems

- Build an ocean worlds software system simulation environment that can simulate the performance of autonomy subsystems and components. Build high-fidelity models of the subsystems and components that will be simulated in the larger system simulation environment.
- Build hardware testbeds to experimentally test autonomy subsystems and components.
- Construct a community V&V certification framework that will assess proposed autonomy systems against the quantified metrics developed above.

Build system and component technologies as described in Section IV. The developments will utilize the defined DRM environments, product breakdown structures, and V&V environments described above.

Part VII: Ocean Worlds DRM Team

The Ocean Worlds Design Reference Mission team is comprised of:
Rebecca Castano, NASA JPL
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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.

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Small Bodies Design Reference Mission Report

Part I: Summary

Introduction

Small bodies, such as near-Earth objects (NEOs), comets, and asteroids are abundant and diverse in their composition and origin. Exploring them is important to advance knowledge in four "thrusts:" decadal science, human exploration, in situ resource utilization (ISRU), and planetary defense. Small Bodies are found all across the solar system and up to the Oort Cloud. Advancements in the aforementioned thrusts depend on: (1) knowing what is where, (2) characterizing the bodies' compositions, (3) understanding their geophysical (including geotechnical) properties, and (4) characterizing their environments.

Autonomy is enabling for Small Body missions because it would allow greater access and enable missions to reach far more diverse bodies than the current ground-in-the-loop exploration paradigm. Operating near, on, or inside these bodies is challenging because of their largely unknown, highly-rugged topographies and because of the dynamic nature of the interaction between the spacecraft and the body. These challenges require autonomy for effective mission operations. Most Small Body missions have used some level of autonomy, but all operated within narrow windows and constraints.

Small Bodies are well-suited targets for advancing autonomy because they embody many of the challenges that are representative of even more extreme destinations, but are accessible by small affordable spacecraft (e.g., SmallSats). Small Bodies are abundant, diverse, and many are within reach to enable a string of missions that not only serve to advance autonomy but are also of inherent value to advance the aforementioned thrusts. Given their diversity, Small Body environments would be unknown a priori and the interaction of a spacecraft near or onto these surfaces would be dynamic for the low-gravity bodies. Technologies developed for autonomous exploration of Small Bodies would have high "feedforward" potential to enable more challenging exploration efforts such as an aerial explorer that canvasses Titan's terrains, dips into its liquid lakes, or sends probes into its ocean-world interior; or an explorer that samples the plumes of Enceladus' Tiger Stripes; or an explorer that ventures into crevasses of Europa, to name a few.

Design Reference Missions

The goal of this Design Reference Mission (DRM) team is to use autonomy to change the paradigm of exploring Small Bodies to one that *enables access to a large number of diverse bodies at affordable cost with minimal human intervention.* The team defined two bold DRMs that autonomy would enable and for which Small Bodies would offer a compelling target for technological advances.

1. **DRM 1: A mission from Earth's orbit to the surface of a Small Body.** This near-term DRM, envisioned for a ~2030 launch, places an affordable SmallSat in an Earth orbit or at Earth-Sun L1 with the high-level goal of reaching a selected asteroid, approaching, landing, accessing a targeted destination, sampling, analyzing the data to target follow-on measurements, and communicating the results of the full investigation back to Earth—all of which would be done autonomously. In essence, demonstration of autonomous exploration capabilities for NEOs would help enable the exploration of other populations such as Trojan asteroids and Kuiper Belt objects (KBOs).
2. **DRM 2: Mother/daughter craft to understand Small Body population.** This long-term DRM**,** envisioned for the 2040s, substantially expands the scope of the first DRM to achieve the goal of the cursory exploration of the entire population of Small Bodies, or at least a large enough sample to have confidence that it is representative. It features a mother/daughter architecture of satellites in Earth's orbit to scan, identify, characterize, and eventually enable access to a range of Small Bodies. The mother craft would dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar objects or hazardous objects). These daughter craft would visit the targets to collect samples and return material to the mother craft for further analysis or for resource extraction. The mission would also be capable of diverting potentially hazardous asteroids, if necessary.

Comparison to State of the Art

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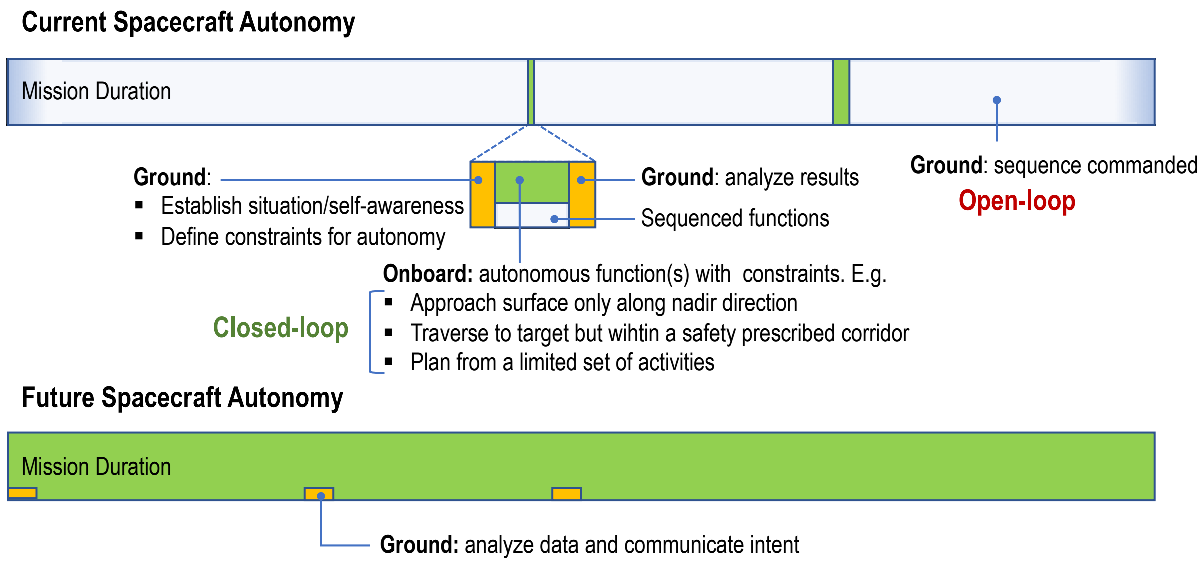

***Figure 2**: Spacecraft autonomy today and in the future*

Building up a fully autonomous capability to access and operate on Small Bodies is a paradigm shift from the current approach, several elements of which are accomplished with some autonomous capability. Examples of autonomous functions for Small Bodies include: autonomous navigation for short durations, elements of fault management, and limited untargeted autonomous surface mobility (Figure 1). With the current practice of deploying one expensive mission at a time through carefully pre-planned explorations, the pace of exploration will remain modest. However, deploying highly autonomous spacecraft, together with advances in spacecraft bus technology (propulsion, computing, sensing) would expand access to Small Bodies. These DRMs aim at bold, yet measurable and fieldable, advances to facilitate the paradigm shift.

Critical Autonomy Technologies for DRM 1

Situation-awareness | **Self-awareness** | **Reasoning and Acting**

- Spacecraft **guidance** and **navigation** with trajectory correction maneuvers
- Unknown body rotation, shape, and gravity **estimation** during approach
- **Hazard assessment** (debris or orbiting moons) near and on the body (gas vents, rough topography, boulders) for safe and precise landing
- Surface, and possibly interior, **composition characterization** and **regolith property characterization** for mobility and sampling
- Landing **site selection** based on safety and value for investigation
- Proximity-maneuver **planning and control** for landing
- Surface **mapping**, **hazard assessment,** and **mobility** to selected targets
- Shallow **manipulation** of unknown/rugged surface for measurements
- Spacecraft **health management** throughout all phases
- **Spectral data analysis** assessing quality and interpreting data; **selection** of future measurements and targets; **calibration, pointing, and placement** of instruments; **returning results** to Earth (through all phases)

Supporting Technologies for DRM 1

The key supporting technologies to achieve the near-term DRM are:

1. **SmallSat** propulsion with ΔV > 1,000 m/s[12] (excluding Earth escape velocity)
2. **Advanced onboard computing and storage:** low-power, low-mass, high-throughput computing with specialized processing for computer vision and possibly neural networks for machine learning to enhance predictive models of the environment
3. **Advanced sensing and optics:** low-power, low-mass, high-resolution miniaturized cameras with variable zoom optics and spectrometers
4. **Surface mobility** and **subsurface mechanisms**
5. **Communication:** low-mass, low-power, direct-to-Earth communication from SmallSats

Findings regarding DRM 1

To realize this vision, this DRM team recommends the following actions:

1. Establish a one-year project with participation from NASA/industry/academia *to flesh out the design details, assess the applicability of external technologies* (automotive and logistics industries/government agencies) *and identify detailed gaps, provide specification for supporting technologies* including rapid systems engineering, and estimate cost of developing and verification and validation (V&V) of the various capabilities.
2. Define crisp engineering challenges to seed solicitations for:
   - Developing a high-fidelity, end-to-end, physics-based simulation to support the development of a fully autonomous mission to a Small Body using SmallSats.
   - Developing and maturing the key autonomy technologies using the full lifecycle simulation.
3. Establish a project to integrate hardware and software capabilities, test them in simulation, and mature them for flight demonstration
4. Demonstrate capabilities of increased sophistication through a couple of SmallSat missions and/or extended missions of opportunity

Success Metrics for DRM 1:

A program to achieve the near-term DRM initially in simulation and later through flight missions could involve the following metrics:

- A SmallSat mission with ΔV of 0.8 – 1 km/s that launches, cruises, and reaches (fly by and images) a small body destination without ground-in-the-loop
- Ability to autonomously approach, rendezvous (ΔV of 5 – 10 km/s) and map a Small Body
- Ability to select a landing site and land
- Ability to transform the approaching craft to a surface mobile platform or deploy a mobile asset and collect samples

---

[12] Based on preliminary analysis of accessible known targets, there are over 600 bodies that would require ΔV < 1,000 m/s to reach

- Ability to analyze spectral data to drive future sampling and resource extraction

Value to NASA:

Space exploration is an endeavor with numerous challenges and constraints. Autonomy could prove to be a pivotal technology that establishes a new paradigm of exploration. To usher in this new era, a systematic and focused approach is needed for a sustained development program to overcome the multitude of challenges. As such, it is critical for the program to be affordable and with easy-to-evaluate success-milestones. Not only would these technologies advance the Small Body thrusts, they would have strong "feedforward" benefit for missions to more challenging and remote planetary destinations including visiting a nearby exoplanetary system. Some of NASA's challenges remain unique, e.g., venturing into unknown and bizarre worlds with no a priori data to learn from and with no opportunity to change the design or fix the craft once launched. However, a vast array of technological advances exists today at NASA and in industry that could help NASA advance its mission. The challenge lies in properly architecting the spacecraft of the future and in closing these technical gaps.

Supplemental Information: DRM 2, Long-term (2040+ DRM)

Critical Autonomy Technologies for DRM 2

Situation-awareness **Self-awareness** **Reasoning and Acting**

- All technologies for DRM 1 +
- Onboard **identification**, tracking and **trajectory estimation** of Small Bodies **based on intent**
- **Trajectory planning** for heterogenous daughter craft
- **Multi-craft coordination**
- Large-scale **manipulation** of **unknown material**
- **Resource extraction**
- **Rendezvous** and **docking** with mother craft **and refueling**

Findings regarding DRM 2

The Small Bodies DRM team finds that the following actions and activities would facilitate implementation of DRM 2.

1. Hold off on DRM 2 until substantial progress is demonstrated under DRM 1 (DRM 2 fully subsumes DRM 1)
2. Following demonstrated in-space capabilities of DRM 1, start fleshing out the details of DRM 2 based on technologies at the time
3. Define concrete plans for ISRU and planetary defense
4. Work with academia to advance fundamental technologies and with industry to mature technologies and realize them in flight
5. Establish these important capabilities for the safety (diverting bodies) and knowledge (science and human exploration) of the Nation and the world

Success Metrics for DRM 2:

For the long-term DRM (2040+), a larger craft with ΔV of 1 – 10 km/s would be able to reach farther destinations and handle larger amount of material. DRM 2 would involve all of the success metrics for DRM 1, plus the following:

- Ability to access well below surface
- Ability to extract resources
- Ability to adequately alter the trajectory of a body for planetary defense purposes
- Ability to fly through and sample a plume on a comet

Part II: The Case for Small Bodies

Introduction

Small bodies comprise many types including near-Earth objects (NEOs), short- and long-period comets, main-belt asteroids, Jovian Trojans, trans-Neptunian objects, and more. These objects are numerous[13] and varied in terms of *location*, *composition*, and *physical properties*. Therefore, when discussing and developing potential Design Reference Missions (DRMs), the Small Bodies DRM team concentrated on the issues that potential Small Body missions have in common.

Why Small Bodies?

Small bodies are valuable targets for:

- decadal science,
- human exploration,
- in situ resource utilization by the public and private sectors, and for
- planetary defense.

Although several missions have focused, or will focus, on Small Bodies, these objects are so numerous and so diverse that they can be used to address a wide range of topics. The objects range from volatile-rich comets that are likely remnants of planetary formation to metal-rich asteroids that are likely the remnants of the cores of planetesimals. Small Body locations range from Earth-crossing orbits, where they are simultaneously attractive targets for resource utilization and potential hazards from a planetary defense perspective; to objects like Centaurs and Jupiter Trojans, whose orbits suggest that they hold keys to the early dynamical history of the solar system; to trans-Neptunian objects that are likely to hold clues to the formation of the outer planets. The objectives of Small Body research include obtaining the following information:

Table 2. Science Objectives

Objectives	**State of the Art**
What is where: the locations of the various bodies can inform us about a. the origin of the solar system: how did it form?	Current knowledge of the architecture of the solar system is primarily derived from surveys using ground-based telescopes, with some space-based surveys, most notably the NEOWISE program (Wide-field Infrared Survey Explorer [WISE] extended mission). The Origins, Spectral Interpretation, Resource Identification, Security-

[13] For example, there are approximately 800,000 numbered asteroids alone.

Objectives	State of the Art
b. the architecture of the solar system: how did it end up in its current state?	Regolith Explorer (OSIRIS-Rex) mission was the first spacecraft to try to survey a region poorly accessible from Earth, searching for Earth Trojans while passing near the Earth's L4 Lagrange point[14]. Although none were found, other regions, including planetary Trojans, irregular satellites of giant planets, and even Kuiper Belt Objects, could best be searched by nearby spacecraft that are autonomous enough to conduct the kind of survey that is now done with humans in the loop[15].
Composition of the body: volatiles like water–a precursor to life on Earth (not looking for life on Small Bodies, but for the source of such molecules) a. Astrobiology b. Formation c. Resources (the most valuable, the least complex to extract)	For most Small Bodies, if there is any compositional information, it comes from spectroscopy, usually infrared, which can be used to detect molecules (for comets) and minerals (for asteroids). In most cases, the spectroscopy is ground-based, although some spacecraft missions, most notably Rosetta, Dawn, and OSIRIS-REx, have also carried spectrometers. In some cases, such as Near Earth Asteroid Rendezvous (NEAR) Shoemaker at Eros and Dawn at Vesta and Ceres, missions have used gamma-ray and neutron spectroscopy to determine major element composition. For trace elements, knowledge is limited to returned samples and to inferences from meteorites that are matched, with varied degrees of confidence, to particular asteroids or types of asteroids.
Geophysical properties of the body a. Current and past processes b. Interaction (crewed and robotic) with and stability of the surface	Knowledge of geophysical properties is extremely limited. In a few cases (NEAR Shoemaker, Hayabusa, Hayabusa2, Rosetta, and soon OSIRIS-REx), a spacecraft has either touched a surface or has deployed a lander, but the geotechnical information has been only a byproduct of studying the interaction, rather than the result of dedicated studies. Bulk properties, such as density and porosity, can be inferred from missions that spend extended periods of time near small bodies, but even then, it cannot be determined whether the porosity is at a macroscopic or microscopic scale. Properties such as

[14] S. Cambioni et al. (2018) *49th Lunar and Planetary Science Conference*, Abstract #1149.
[15] New Horizons spacecraft has conducted searches for KBOs in that vicinity

Objectives	State of the Art
	cohesiveness have never been studied, except to the extent that meteorites serve as analogs.
Characterizing the environment a. Atmospheres, particles, and fields (includes outgassing) b. Potential presence of hazards for crewed and robotic missions c. Spatial and temporal temperature distribution d. Radiation	Small Bodies environments vary wildly. Knowledge of atmospheres comes in large part from spectroscopy. Cometary bodies offer all types of environmental challenges, including the ejection of meter-sized blocks. Airless bodies, especially Small Bodies, may be surrounded by dust ejected by micrometeorites and/or regularly lofted as a consequence of electrostatic charging. These factors may represent potential hazards and require characterization during approach. Thermal mapping from orbit is needed for landing site selection (both from an energy management standpoint and for inferring regolith structure for landing and mobility).

What Small Bodies?

The particular mission goals determine the appropriate type and size of the body to target. The size of Small Bodies can span meters to several thousand kilometers. In this Small Bodies DRM team, our focus is on bodies that range from meters to only tens of kilometers in size, where there is just enough gravity[16] to make operations on the surface particularly challenging: enough gravity that its effects have to be considered in maneuvering and operating, but not enough gravity to be able to remain in a safe orbit for extended periods of time without actively adjusting and monitoring location and not enough gravity to safely anchor to the surface of the body. Missions to larger and more remote bodies, such as Pluto and Ceres, would still benefit from many of these technologies, but would need further advances to enable more timely response dictated by the higher gravity and challenging topographies. Additional technologies for such bodies are also addressed by the Ocean Worlds DRM team.

Table 3: Highlights of autonomy advances across Small Body missions (past and current)

	Demonstrated Autonomy Advance	Capability/ Technology	Key Gaps and Needed Capabilities

[16] For bodies of meters to tens of kilometers gravity can range from 10^{-6}g – 10^{-3}g

<table>
<tr><td>1998 – 2001
Deep Space I</td><td>Cruised autonomously for 3 of 36 months (<10%);
30-minute autonomous flyby</td><td>Planning/scheduling
Autonomous navigation (asteroid detection, orbit update, spacecraft low-thrust Trajectory Correction Maneuvers or TCMs)
System health management</td><td rowspan="6"><u>Key Gaps</u>
▪ Limited scope of autonomy use: capabilities have only been used for relatively short durations of the mission with pre- and sometimes post-monitoring from ground.
▪ Use of a priori maps: missions with proximity operations required extensive ground processing to generate maps that were used in subsequent autonomous maneuvers.
▪ Reliance on ground-based resource planning

<u>Needed Capabilities</u>
▪ End-to-end, long-duration autonomy
▪ Autonomy in light of faults and failures
▪ Autonomy in environments with large uncertainties and limited a priori knowledge of the environment
▪ Autonomy that can handle a wide range of conditions, adapt and learn from its operations</td></tr>
<tr><td>2002– 2011
Stardust</td><td>30-minute autonomous flyby of one asteroid and two comets</td><td>Target-body detection (one body)
Attitude updates for tracking nucleus through flyby</td></tr>
<tr><td>2005 – 2010
Deep Impact</td><td>Two-hour autonomous terminal guidance of comet impactor
Flyby tracking of two comets</td><td>Target-body detection (one body), orbit update, and spacecraft low-thrust TCMs</td></tr>
<tr><td>2005
Hayabusa</td><td>Autonomous terminal descent of last 50 m toward a near-surface goal for sample collection</td><td>Laser ranging (at < 100m) to adjust altitude and attitude</td></tr>
<tr><td>2019
Hayabusa2</td><td>Same as Hayabusa</td><td>Same as Hayabusa; bright surface object detection and centroiding; hybrid ground/onboard terminal descent control: ground controls boresight approach, while onboard controls lateral motion in final 50 m; on surface, open-loop control of surface hopping mobility</td></tr>
<tr><td>2020
OSIRIS-REx</td><td><u>Potential plan:</u> terrain-relative navigation (TRN) for touch-and-go maneuver</td><td>Uses ground-generated shape-model, match natural features to model using TRN with ground oversight; onboard final maneuvers to initiate touch-and-go for sample collection</td></tr>
</table>

2022 Double Asteroid Redirection Test (DART)	Several hours of autonomous terminal guidance (similar to Deep Impact)	Identification of each body for target selection; thruster control to guidance impact; targeting the 170-m moon of a 780-m primary	

Autonomy in current and planned missions to Small Bodies

To date, only five missions have attempted to operate for extended periods of time in close proximity to such Small Bodies: Shoemaker, Rosetta, Hayabusa, Hayabusa2, and OSIRIS-REx. The difficulties encountered by Rosetta's Philae lander and by the first Hayabusa mission highlight how much we do not know about these bodies. Most of these missions relied (or will rely) on autonomy to some degree, because of the obvious challenge of operating on or near a poorly understood surface at a distance of even a few light-minutes from Earth. Given the diversity of Small Bodies, it is likely that many more missions will have to be flown before we are likely to have experienced the range of surface properties we might encounter.

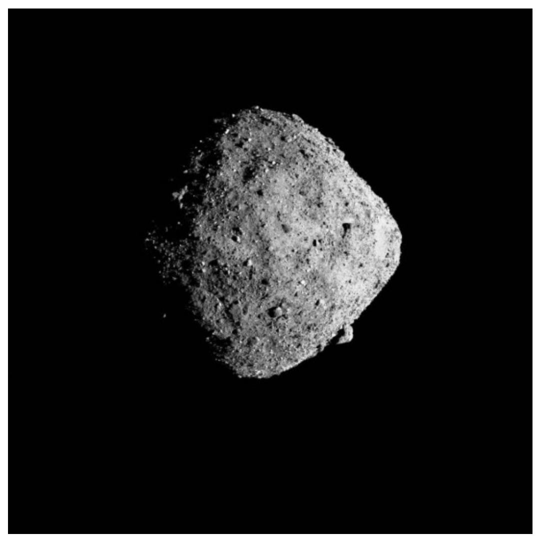

Figure 3: *Bennu, as imaged by OSIRIS-REx (NASA, Goddard Space Flight Center, University of Arizona). Note the large number of boulders.*

In addition, there have been numerous missions that have performed flybys of Small Bodies, beginning with the flyby of Halley's comet in 1986, followed by the Galileo mission's flyby of Gaspra in 1991. In many cases, such flybys have been en route to other mission targets, and the spacecraft have not attempted close flybys. But in some cases, most notably the recent New Horizons flybys of Pluto and 2014 MU_{69} and the upcoming Lucy flybys of Jupiter Trojans, the flyby is the heart of the mission, and occurs at high velocity at a relatively large light travel time from Earth. New Horizons did not use autonomy for its flybys, and the decision for Lucy has yet to be made. However, it is clear that in cases like these, spacecraft with the capability to autonomously acquire the target object and manage both the nominal trajectory and the complications that could arise from previously unknown natural satellites or debris in the vicinity of the target, would enable better-targeted and closer approaches, yielding higher-resolution data.

Why is autonomy enabling for Small Body missions?

The limited use of autonomy has already proven essential for current missions to Small Bodies, in particular, for fast flybys and touch and go (TAG) for sample collection. More capable autonomy will make it possible to reach and explore a wider range of diverse bodies, conduct more in-depth investigations of their heterogeneous compositions, and develop a better understanding of their origins. Autonomy is enabling for small bodies because they are:

1. **Abundant and Diverse:** There are numerous and diverse destination options and autonomy would enable more access and exploration of these disparate and diverse bodies. As of early 2019, there are approximately 800,000 known asteroids, more than 2,000 Kuiper Belt Objects, and various other populations of Small Bodies. These objects can be classified by telescopic observations into groups that are almost certainly chemically distinct. Furthermore, even among bodies that are genetically related, there may be intact planetesimals, differentiated interiors, disruption fragments, and rubble-piles of reaccreted material, all representing different sets of processes. Hence, the number of different histories experienced by Small Bodies and the number of different pieces of solar system history accessible to study is extremely large among known Small Bodies. While it is easily possible to develop a mission to a single body, exploring this diverse population can be done most rapidly by employing many spacecraft, each of which can explore multiple bodies. With an eventuality of numerous spacecraft exploring numerous destinations and given limited communication windows, such assets would have to rely on onboard decision-making for local (within a body) and remote (other bodies) situations, evolving the role of ground control to the higher-level management of the parallel missions.
2. **Operationally Challenging:** Small Bodies have very rugged topographies with unknown surface compositions and a priori unresolved rotation and gravity parameters. The interactions of a spacecraft in proximity[17] of a Small Body, on its surface, or below its surface, all require resolving the body's motion parameters, understanding its non-uniform surface composition and gravity, and understanding its interior formation. Autonomy would enable:

[17] Interactions near (within ~50 m), on or into the surface are particularly challenging due to low gravity, surface roughness, and the dynamic nature of the interaction

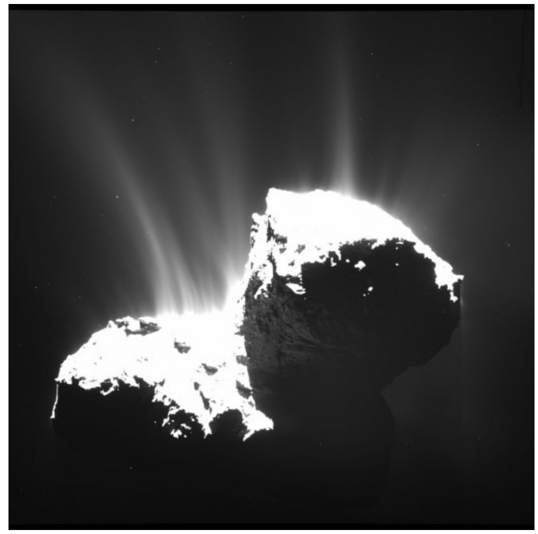

***Figure 4**: Rosetta image of Comet 67P/ Churymov-Gerasimenko, showing material venting from surface (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA /UPM/DASP/IDA)*

a. **Proximity Interaction:** Exploration near, onto, or into the surface requires an understanding of the dynamic interaction between a spacecraft and the a priori unknown low-gravity body. Autonomy would enable such dynamic interaction where models would have to be generated and reasoned about and where decisions would have to be made in real time[18]. These scenarios include final-descent phase of a spacecraft onto a Small Body, interaction with the body to understand its surface properties for both science or engineering purposes, or managing a robotic mechanism for mobility or sampling.
b. **Handling the environment:** In addition to the challenges of the irregular topography and low-gravity environment, some Small Bodies, such as comets, generate dynamic conditions from outgassing or block-ejection events (e.g., images of Hartley 2 during the EPOXI flyby revealed meter-sized ice blocks being ejected). Such conditions have to be monitored and avoided in real time.
c. **Reaching specific surface targets:** Reaching multiple and specific destinations on the surface of Small Bodies within specific timeframes is unlikely to be possible without autonomy. Reaching larger numbers of objects likely means accessing smaller objects, many of which may not be visible from Earth, and thus their basic physical properties may not be available to support an in situ mission. These destinations can be either densely or sparsely specified and can be targeted for measurement during specific time windows. Accessing the surface, whether to make seismic or ground-penetrating radar measurements of an asteroid, to approach a vent of a comet, or to sample any of these bodies, would require an interaction that cannot be reliably planned a priori.
d. **Manipulating the surface or subsurface:** Autonomy is required for resolving sample properties for collection (e.g., grain size) and for anchoring or holding onto the surface, which is based on instantaneous local conditions.
e. **Extracting resources:** Exploration in search of resources would likely require anchoring to and reaching meters below the surface. Extraction would require deeper access.

[18] The paradigm of planning actions of a spacecraft days or weeks in advance—while highly successful for flyby or orbiting missions due to ability to predict based on orbital dynamics—starts breaking down when interacting with an unknown environment, where models of such interactions are not available. Even the quasi-static surface exploration of Mars and the Moon have shown that for effective mobility, maneuvering and interacting with the surface, autonomy has become increasingly critical.

Such interaction would require reacting to local conditions to ensure proper grasp and effective extraction while handling anomalies due to interacting in a granular media environment.

f. **Planetary defense:** Planetary defense requires understanding the composition and geotechnical properties of Small Bodies. Mitigation would require dealing with a largely unknown interior and surface that would best be approached with autonomous spacecraft. Furthermore, several deflection scenarios, such as a kinetic impactor or gravity tractoring, require the spacecraft to navigate autonomously due to the need to adjust the trajectory in real time.

3. **Enabled by Agile and Opportunistic Spacecraft:** Because of the wide array of sizes, locations and properties, large-scale exploration of Small Bodies can be achieved far more efficiently with a fleet of spacecraft. Each spacecraft could have limited capabilities but could be retargeted multiple times. Furthermore, such spacecraft might be retargeted to objects whose existence was not known at the time of launch.

B. Why are Small Bodies suitable targets for advancing autonomy?

Small Bodies, in particular NEOs, are well suited to advance autonomy because they embody many important attributes and challenges to overcome that are representative of bodies that are more distant. Small Bodies are suited to advance autonomy because they are:

1. **Abundant, Accessible and Affordable to Explore:** There are numerous nearby Small Bodies that can be reached with small and affordable spacecraft. Given their abundance and proximity to Earth, Small Bodies offer frequent yearly launch opportunities. Once outside Earth's gravity well, spacecraft can fly by one of hundreds of Small-Bodies by using ΔVs of less than 1 km/s and rendezvous with one using ΔVs of less than 5–10 km/s. Given their low gravity, Small Body surfaces can be reachable with low-power landing systems for trajectories with low-enough approach velocity. Descending on Small Body surfaces can be relatively slow and is unencumbered by the presence of an atmosphere that introduces additional uncertainty. The ability to use small spacecraft to reach Small Bodies and their surfaces make such objects affordable targets for both advancing the technologies and reaping the scientific and commercial benefits. There are approximately 20,000 Near Earth Objects[19] (NEOs); most are asteroids, but some are comets. There is currently no available database listing potential one-way missions[20] to NEOs, but a database for round-trip missions (https://cneos.jpl.nasa.gov/nhats/) lists more than 250 objects for which a round trip could be accomplished with a total ΔV from Earth orbit of less than 6 km/sec and a round trip of less than 450 days, without considering mid-course corrections, gravity assists, or continuous thrusting (e.g., electric propulsion).

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[19] NEOs are small Solar System bodies with orbits around the Sun that are, at some point, between 0.983 and 1.3 astronomical units from the Sun. NEOs are not necessarily currently near Earth, but their orbits can potentially become Earth-crossing.

[20] A database for one-way missions is in development for access by robotics missions

2. **Scalable:** Small Bodies' accessibility and affordability lend them to missions that employ multiple spacecraft and spacecraft that can reach multiple destinations.

3. **Adequately challenging:** Small Bodies offer a unique balance between the a priori unknown environment and a low-gravity environment that drives a dynamic interaction with that body; the slow dynamics result in a more forgiving environment that minimizes the severity of impact with the surface. As such, Small Bodies offer a stepping stone toward the more complex dynamic of landing on larger bodies with largely unknown atmospheres.

Although the primary DRM discussed below is for a mission to a NEO, the autonomy technology needed would be enabling for missions to other Small Bodies. In particular, the more distant an object is from Earth, the longer the light-travel time for commands and data to move back and forth, and the more autonomous systems will enhance the mission. Safe near-surface navigation is critical for any mission involving a lander or rover, but that can only be done with autonomy due to the low gravity and the dynamic Small Body environment. And the more capable the autonomy, the more difficult (and more interesting) the target landing site can be. Once a mission lands or anchors on a Small Body, safe operations while moving, or while manipulating the surface or near-subsurface, can only be done very slowly, if at all, without autonomy. Even for less complex flyby missions, autonomy will make it possible to target closer flybys, by providing a means to search for and mitigate or avoid hazards in the form of moons, vents, etc.

Advancing autonomy for Small Bodies would advance and prove in-flight capabilities that could be used for other mission scenarios, such as the aerial exploration of Titan or Venus or the surface exploration of Enceladus and the sampling of its active plumes.

Part III: Design Reference Missions

The Small Bodies team developed two DRMs: (1) a relatively near-term DRM that could be accomplished in the 2030s timeframe and a (2) futuristic long-term DRM that would unlikely be accomplished before the 2040s. The ultimate goal is to accomplish a cursory exploration of the entire population of Small Bodies, or at least a large enough sample to be representative, and the futuristic DRM lays out a scenario to accomplish such a formidable challenge. The futuristic DRM subsumes the near-term DRM and expands its scope. This report primarily concentrates on detailing the near-term 2030 DRM, in keeping with the purpose of the NASA 2018 Workshop on Autonomy, and will only briefly touch upon the long-term DRM.

Autonomy is needed for both DRMs for the following reasons:

- To interact near (50-meters), on, or delve into the body's surface (e.g., for final descent, to understand surface properties, to manage a robotic mechanism to achieve mobility and interaction)
- To react to the dynamic environment conditions
- To access specific destinations in specific time frames and target areas for sampling and analysis
- For manipulation: to resolve sample properties in real time and react dynamically to surface conditions
- To collect samples (e.g., operating near a vent on a comet)
- To learn more about ISRU (will likely need to explore below the surface and possibly extract)
- For planetary defense: to understand the threat and how to interact with the Small Body

In addition, autonomy will enable scalability (the ability to explore numerous different destinations at multiple times or even simultaneously) through reduced costs, and agility (the ability to rapidly access various Small Bodies).

DRM 1: A mission from Earth's orbit to the surface of a Small Body

Synopsis: The mission places an affordable SmallSat in Earth's orbit with a high-level goal of reaching a selected asteroid, approaching, landing on the body, precisely accessing at least one target on the surface, sampling, analyzing the measurements, retargeting follow-on measurements based on local analyses, and sending the publication[21] back to Earth, all of which would be done autonomously.

Benefits: The benefits include addressing the science objectives in Table 1 and contributing information that informs planetary defense and in situ resource utilization. For planetary

[21] While the comment about autonomously producing the publication is said "tongue-in-cheek," the goal would be to produce data of the quality expected of publishable results, enabling explorers to focus on higher-order goals.

defense, such a mission could assess the threat to Earth (determining position, mass, properties of the body) and inform any mitigation strategies (e.g., how will the body react when we try to move it?). For ISRU, it would determine whether the body contains any resources of interest and how they could be accessed.

Related Work: Similar missions have been proposed or studied in the past, most notably the Primitive Object Volatile Explorer (PrOVE) mission[22] that is the subject of a Planetary Science Deep Space Small Satellite (PSDS3) study, which would have parked at an Earth Lagrange point and targeted a passing new comet.

At present, all missions to Small Bodies have been launched with a specific target in mind, requiring specific launch windows. In fact, it is hard to envision a scenario in which that is not the most effective approach for a spacecraft near Earth. However, in a future in which the starting point might be anywhere in the Solar System (for example, at the conclusion of an exploration of one body, when the spacecraft is ready to be used somewhere else), autonomy in mission design would be enabling.

Assumption(s): the following supporting capabilities are assumed:

- Computing capability for establishing necessary situational awareness of the environment and reasoning about situation and self.
- Miniaturized instruments such as imagers, spectrometers, radar, or whatever else this pathfinder mission would need.
- Capable propulsion: propulsion with enough ΔV to enable access to a reasonable number of Small Bodies. For a pathfinder study such as this, the knowledge gained from studying any Small Body would represent enough of an advance that target choice could be based on trajectory considerations alone, but a detailed study would need to be done to determine what *ΔV* is required to provide the desired number of launch opportunities. A database of round-trip missions[23] documents several NEOs for which the total required *ΔV* is less than 5 km/s, and for a one-way trip, there are NEOs accessible with *ΔV* less than 1 km/sec.

DRM 2: Mother/Daughter Craft to understand the Small Body Population

Synopsis: The mission places a centralized mother platform with multiple daughter satellites in Earth's orbit to scan, identify, characterize, and eventually enable access to a range of Small Bodies. The mother craft will dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar objects or hazardous objects). These daughter craft will visit the targets to collect samples and return material to the mother craft for further analysis or for resource extraction.

Benefits: The ultimate goal is cursory exploration of the entire population of Small Bodies, or at least a large enough sample to have confidence that it is representative. If this goal is

[22] Primitive Object Volatile Explorer, https://www.hou.usra.edu/meetings/smallsat2018/pdf/14_Hewagama.pdf
[23] https://cneos.jpl.nasa.gov/nhats/intro.html

approached one mission at a time, through carefully pre-planned explorations, there will be progress, but not at the pace that could be achieved with highly autonomous systems. The benefit here is to *affordably explore a large number of diverse* Small Bodies with minimal human intervention and minimal communication with Earth. Given the diversity of Small Bodies, which ones are first to be explored is not important, although characterization of the body to be explored becomes more important as the number explored grows. This DRM would result in a more comprehensive understanding of Small Bodies for science, ISRU, and planetary protection—including knowledge that will eventually enable diverting Small Bodies, if necessary. To truly explore the diversity of Small Bodies, it is most efficient to have each spacecraft involved explore as many bodies as possible. If there is no need for samples, the spacecraft could utilize resources identified along the way. However, if samples are to be returned anyway, it provides an opportunity to refuel for spacecraft that are not going to volatile-rich bodies, allowing more flexibility in the design of the system.

Related Work: The science objectives of this DRM are similar to the near-term DRM described above, but increased autonomy further expands the capabilities of the mission (e.g., by increasing the diversity of Small Bodies that can be investigated). In some ways, this DRM is a greatly expanded version of missions like the proposed Main-belt Asteroid and NEO Tour with Imaging and Spectroscopy (MANTIS)[24] Discovery mission, intended to study nine NEOs and main-belt asteroids, albeit with a single spacecraft.

Assumption(s): in addition to the assumptions listed for the near-term DRM, this DRM would require:

- Material extraction tools (including some deep-sampling tools for resource extraction)
- **Low-power communication among spacecraft** for communication among daughter craft and between daughter craft and mother craft

[24] Main-belt Asteroid and NEO Tour with Imaging and Spectroscopy, https://ieeexplore.ieee.org/document/7500757

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.

Autonomy Capabilities needed for DRMs 1 and 2

Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+) Coord multiple assets	DRM 2: Identify target bodies	DRM 1: Near-term (2030) Design mission	DRM 1: Cruise	DRM 1: Characterize body	DRM 1: Approach	DRM 1: Land safely	DRM 1: Land at target	DRM 1: Move on surface	DRM 1: Analyze subsurf.	DRM 2: Manipulate surface	DRM 2: Refuel / ISRU	DRM 2: Return to mother	DRM 2: Refuel mother
Identify Body pre-Cruise	Identify target body based on intent	Monitoring and **identification** of Small Body **targets based on a priori defined criteria.** **Reasoning and selecting among** multiple candidate **target bodies based** on an a priori identified criteria		**Situation Awareness** 1.1 Sensing and Perception 1.5 Event and Trend Identification **Reasoning and Acting** 2.1 Mission Planning and Scheduling	■	■	■	■										
Identify Body pre-Cruise	Estimate body's trajectory	**Target detection** and **tracking** from millions of km distance; defining models for objects' motions		**Situation Awareness** 1.1 Sensing and Perception 1.3 Knowledge and Model Building			■	■										
Identify Body pre-Cruise	Design mission trajectory	**Sensing, perception and estimation** of small body trajectory from an Earth orbit or an Earth-Sun L1 **Trajectory planning** to reach a Small Body given spacecraft capabilities and onboard resources		**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building			■	■										
Cruise	Cruise to target vicinity	**Execution of** planned spacecraft, orbit determination and trajectory correction maneuvering	Y	**Reasoning and Acting** 2.1 Mission Planning and Scheduling 2.2 Activity and Resource Planning … 2.4 Execution and Control				■										
Model	Identify body's rotation parameters	**Feature/landmark detection** and **tracking** that are robust to shape, surface texture, lighting, rotations **Pose and rate estimation** of body rotation (periodicity, center of rotation, axes of rotation and nutation)	Y	**Situation Awareness** 1.2 State Estimation and Monitoring						■	■	■	■					

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Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
					Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Build 3D model of body	**3D shape reconstruction** (e.g., Shape-from-Silhouette (SfS); Structure from Motion (SfM); photoclinometry)	Y	**Situation Awareness** 1.3 Knowledge and Model Building														
Identify Surface Composition	Identify water content	**Automated calibration**, **parameter setting** and tuning of instruments for remote and in situ measurements with considerations to lighting direction, pointing, and placement (for in situ). **Assessment of quality** of measurements. **Analyses and uncertainty quantification** of spectra to determine presence and abundance of water, elements or minerology within a single spectrum, across multiple spectra, or through an evolving spectrum, (dynamic situation) **Data-driven re-targeting of measurements**: identify signatures of interest and retarget same or other instruments for additional and more resolved measurements (e.g., multi-spectral micro-imager on a positioning device). **Modeling measurement process** to enable reasoning about the acquisition and measurement data	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.5 Event and Trend Identification **Engineering and Integrity** 4.4 Modeling and Simulation														
	Identify elemental composition																	
	Identify mineralogy																	
Identify Interior	Characterize internal heterogeneity and assess large-scale porosity	**Characterize** internal **heterogeneity** via radar, thermal imaging, gravity-field mapping, and seismometry for both science and ISRU. **Assess hazard** due to porosity that can cause major disruption of the body. Needed for deep sub-surface access.		**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building														

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Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+) Cord multiple assets	Identify target bodies	DRM 1: Near-term (2030) Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Map gravity field	Map gravity field to inform close approach and landing as well as interior composition (for science). May need multiple spacecraft for precise measurements. (difficult to do on bodies that are < 10 km; for > 10 km, this would be critical for approaching and landing).																
	Map magnetic field	For science purposes only																
Sense Dynamic Environ.	Assess presence of moons or orbiting debris critical for mission safety during approach	**Sensing and perception and tracking** of potential hazards **Change detection** in the vicinity of or on the body **Assessment of** potential **hazards** on spacecraft	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building 1.4 Hazard Assessment														
	Detect presence of jets of gas, plumes of dusts through vents near or on the body																	
Characterize Body for Landing	Characterize surface albedo and variations	**Characterization of surface albedo:** requires body model, Sun direction **Outlier detection** to identify unique sampling targets in addition to common material targets. **Data fusion:** co-registration from heterogenous sensors at different scales/resolutions (both science, e.g., composition) and engineering instruments (e.g., topography)). Requires global localization in a dynamic environment to identify common material and outliers, both of which are likely targets for sample collection.	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building														
	Assess surface hazards for landing	Characterization of surface slope relative to gravity, roughness, and boulders at the scale needed for landing from approach imagery (depends on spacecraft design but typically at ~20-30 cm)	Y	**Situation Awareness** 1.4 Hazard Assessment														
Appro	Precision targeting	**Planning** spacecraft **approach trajectory** based on models of body motion during approach	Y	**Reasoning and Acting** 2.1 Mission Planning and Scheduling 2.4 Execution and Control														

Table 3: Mapping DRM Capabilities to Functions and Technologies

					DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
Functional Group	**Function**	**Technology Area**	**Critical for DRM 1?**	**Autonomous Systems Capability Leadership Team Taxonomy**	Cord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Approach and landing	**Selection of landing target** based on landing hazard assessment maps, surface and interior composition, and other relevant criteria Guidance and control for 6-Degree of Freedom spacecraft during final approach and landing	Y	**Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.4 Execution and Control						X	X							
Characterize Body for Mobility	Model surface topography	**Construction of 3D surface topography** at a scale to enable surface mobility; co-registration of data from multiple vantage points on surface or near surface*: slope relative to gravity, roughness, and boulders	Y	**Situation Awareness** 1.1 Sensing and Perception 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building **Collaboration and Interaction** 3.1 Joint Knowledge and Understanding 3.2 Behavior and Intent Identification					X		X	X	X	X				
	Characterize surface physical properties	**Characterization of grain-size distribution** (for science, mobility and manipulation), cohesion of surface particles (for operations including manipulation of material, sample handling). Informs surface interaction	Y						X		X	X	X	X				
	Assess surface regolith porosity	**Characterization surface porosity** through contact and surface compression at the scale that will impact mobility and manipulation							X				X	X				
	Observe interaction with surface from standoff distance	**Perception** and **modeling of interaction** between an asset and the surface as observed by another spacecraft from a stand-off distance (e.g., observe DART impact, mother craft observing daughter craft like Rosetta observing Philae).			X										X			
Mobility and Manipulation	Surface Mobility	**Assessment of mobility hazards** (see handling dynamic environment) **Identification of targets** based on surface/subsurface characterization **Surface motion planning** to reach designated target while avoiding hazards **Executing mobility actions** to reach specific destinations within specific timeframes (dense vs. sparse coverage, targeting vs. exploration) **Pose estimation** (relative and absolute position and attitude) of spacecraft. Critical for both engineering and science measurement	Y	**Situation Awareness** 1.4 Hazard Assessment 1.5 Event and Trend Identification **Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.3 Motion Planning 2.4 Execution and Control									X					
	Small-scale surface manipulation	Target selection for sampling; sampling and sample handling Sample **measurements** and **analysis** (see identify surface composition)	Y	**Situation Awareness** 1.4 Hazard Assessment										X				

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Table 3: Mapping DRM Capabilities to Functions and Technologies

Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	DRM 2: Long-term (2040+)														
							DRM 1: Near-term (2030)												
					Coord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	Small-scale plume sampling	**Operating and sampling** from a vent of a comet, where interaction with the vent is dynamic in nature or sampling in the vicinity of the vent where different dynamic hazardous conditions exist		1.5 Event and Trend Identification **Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.3 Motion Planning 2.4 Execution and Control														
Below-Surface Access	Large-scale surface manipulation (e.g. excavation)	Anchoring or holding on to the surface based on estimation of instantaneous local conditions; manipulation of large surface blocks; decomposition of large blocks into manageable entities **Sorting** through large heterogeneous regolith and rocks Deep **subsurface access** and material extraction **Implanting of instruments** (either temporarily or permanently) for anchoring or for diversion for ones that are a planetary defense hazard.		**Situation Awareness** 1.4 Hazard Assessment 1.5 Event and Trend Identification **Reasoning and Acting** 2.2 Activity and Resource Planning and Scheduling 2.3 Motion Planning 2.4 Execution and Control														
	Access 1-2 m below surface for ISRU	**Anchoring** or holding on to penetrate to subsurface **Deep subsurface access** and material extraction Transferring and processing large amounts of material																
Refueling	Refuel spacecraft using in situ resources	Extraction of material, processing, and handling to refuel surface asset using in situ resources (avoids need for return trips to centralized platform for refueling and enables moving from one target body to another with orbits that are progressively harder, which would otherwise be harder to access from Earth)		**Situation Awareness** 1.1 Sensing and Perception 1.5 Event and Trend Identification 1.2 State Estimation and Monitoring 1.3 Knowledge and Model Building **Reasoning and Acting** 2.1 Mission Planning and Scheduling 2.2 Activity and Resource Planning and Scheduling 2.4 Execution and Control 2.7 Adapting and Learning														
	Return to centralized Platform	Return of collected samples to centralized platform for later pick for return to Earth for full characterization in terrestrial laboratories (avoids requiring exploratory spacecraft to re-enter Earth's atmosphere; eliminates the need to have a team to deal with the samples at the time of return)																
	Refuel centralized platform	Return to refuel centralized platform using resources collected from volatile-rich bodies.																
Spac	Monitor and manage health of spacecraft	Fault prognosis, detection, diagnoses and response. Learning and adapting for past spacecraft experience	Y	1.5 Event and Trend Identification 1.6 Anomaly Detection 2.5 Fault Diagnosis and Prognosis														

Table 3: Mapping DRM Capabilities to Functions and Technologies

					DRM 2: Long-term (2040+)													
							DRM 1: Near-term (2030)											
Functional Group	Function	Technology Area	Critical for DRM 1?	Autonomous Systems Capability Leadership Team Taxonomy	Cord multiple assets	Identify target bodies	Design mission	Cruise	Characterize body	Approach	Land safely	Land at target	Move on surface	Analyze subsurf.	Manipulate surface	Refuel / ISRU	Return to mother	Refuel mother
	V&V spacecraft	V&V of autonomous capabilities; test and evaluation through modeling, simulation, test beds and multiple mission	Y	2.6 Fault Response 2.7 Adapting and Learning **Engineering and Integrity** 4.1 Validation and verification 4.2 Test and Evaluation 4.4 Modeling and simulation 4.5 Architecture and Design														
	Ground Systems	On-demand interaction with autonomous spacecraft using ground stations.	Y															

* Need to think about what drives higher accuracy. Some applications may not require that. Perhaps first mission can get away with lower accuracy. At the scale of the lander (typically 20 cm)

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Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
From Earth Orbit (millions of km from Body)	Target identification based on intent	Autonomous detection of vehicles and pedestrians in autonomous transportation	Limited sensed information due to very remote bodies	Advanced computing w/ graphics processing unit (GPU) capabilities Miniaturized high-quality optics High-resolution sensors in visible and infra-red	Autonomous vehicle identification of objects (pedestrians/vehicles) at a distance.	Having highly resolved images at astronomical distances with full coverage Limited sensing and computing onboard SmallSats in Earth's orbit compared to Earth assets	Degree of applicability of industry capabilities. SmallSats in different locations (such as the Earth-Sun L4 or L5 Lagrange points, or at some random location in the Inner Solar System) after studying a particular body, could easily carry technology to be the most effective way to search the surroundings.
	Remote (astronomical distance) target detection with large area coverage	Several surveys devoted to discovery of Small Bodies, mostly searching for Near-Earth Objects, but also for objects as distant as trans-Neptunian objects. Many of these have at least some autonomy in their detection system, but none is fully autonomous at this point.	Fully autonomous target identification from both Earth and in space for remote bodies Identification of objects millions of kilometers using low-mass, low-cost designs		NASA's astrophysics	Onboard capability for detecting and tracking remote objects with weak signals	
	Estimation of trajectory of target body				Ground-based navigation tools (e.g. NASA Jet Propulsion Laboratory [JPL] Mission Analysis, Operations, and Navigation Toolkit Environment [MONTE] [10])	Limited observations with limited sensors and optics at large distances	
	Planetary trajectory planning	Ground-based process with human experts in the loop	Onboard trajectory planning with associated ephemeris information	Ground-based trajectory planning tools Advanced computing	None	Capturing human expertise in trajectory design into codified algorithms. Complex space with numerous options with multiple optimization criteria	
	Cruising to target body vicinity	Ground-based radiometric and optical navigation. Autonomous optical navigation used on Deep Space 1 [2]	End-to-end autonomy that handles constraints, resources and health	Affordable and low-mass propulsion with $\Delta V >> 1$ km/s	Industrial development of propulsion technologies; small R&D and flight efforts but with limited scope	Requires robust reasoning to handle a range of conditions and avoid critical failures	
On Approach	Landmark-based feature tracking	Ground-based manually-intensive terrain-relative navigation using Stereo-Photoclinometry (SPC)	Automated landmark extraction. V&V of feature tracking algorithms	Advanced computing w/ GPU capabilities Miniaturized high-quality optics High-resolution sensors in visible and infra-red	Simultaneous Localization and Mapping (SLAM) techniques from robotics domain Machine learning for robust feature tracking	Robustness to lighting changes, long sharp shadows, low-albedo and occlusions Achieving low-uncertainty in estimation	Currently, these tasks require heavy ground-in-the-loop analysis, often with multiple teams

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Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Pose and pose rate estimation	Ground-based data fusion: reconstruction using SPC-based shape models [11]; star trackers for spacecraft attitude changes, Deep Space Network (DSN) range/rate and far-field asteroid imagery for orbit determination.	Autonomous relative navigation between spacecraft and body and using onboard feature tracking V&V testbed	Estimation filtering techniques	NASA orbital ground-based navigation techniques SLAM techniques from robotics domain [12]	Robust landmark targeting and low-uncertainty using efficiency onboard algorithms	Currently, these tasks require heavy ground-in-the-loop analysis, often with multiple teams
On Approach (1,000+ – 1+ km)	Object 3D Modeling	Ground-based manually-intensive model reconstruction using SPC-based [3] and Stereo-based Photogrammetric (SPG) approaches [4].	Onboard autonomous shape reconstruction with ability to handle uncertainties in spacecraft pose, body rotation, and lighting variations	Advanced computing Data representations	3D scanning and model building; Shape-from-silhouette; Extensive real-time point-cloud mapping in terrestrial robotics applications / self-driving cars	Data fusion across large scale changes that is robust to different body rotations, geometries, albedo and lighting conditions	Currently, these tasks require heavy ground-in-the-loop analysis, often with multiple teams
	Rendezvous guidance and control	Flyby and impact missions use narrow angle camera for relative pose estimation. Autonomous correction maneuvers for targeted impact/flyby (e.g., DART's SmartNav system)	Control of low-thrust maneuvers for precision rendezvous. Control of single large arrival burn maneuver.	SmallSat propulsion systems. High-quality NavCam Optics for SmallSats.	Industrial development of propulsion technologies;	Managing uncertainties to avoid collision with body	
Instruments (1	Spectral instrument parameter setting	Manually tuned settings by instrument experts	Autonomous tuning and parameter setting	Signal processing Machine learning Miniaturized low-power instruments that are robust to a wide range of environmental conditions	Ground-based automated tools used in missions	Capturing human experience of operating instruments in relevant environment	

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Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Spectral analysis (and uncertainty quantification)	Manually analyzed on the ground to characterize Small Bodies (Hayabusa, Rosetta, Hayabusa2, OSIRIS-REx, and NEAR Shoemaker*)* Interior composition inferred from gravity field	Autonomous characterization of bodies Direct measurement of interior composition	Knowledge databases for interpreting and reasoning about measurements Instrument capable of subsurface measurements	Defense Advanced Research Projects Agency (DARPA) Program: Artificial Intelligence for Chemistry (for data analysis) Currently used ground tools for spectral analysis	Onboard, computationally-efficient, expert-informed analysis databases and tools	Whether the basic characterization done by mission science teams can be adapted to be done autonomously.
	Science-data decision-making	Carefully-orchestrated measurement campaigns for in situ science, often planned weeks in advance. Changes to campaigns occur only after ground-based analysis of the data returned shows that either some measurements do not meet the mission's requirements or some measurement(s) indicates an unanticipated phenomenon.	Onboard interpretation and understanding of measurement analyses to inform subsequent commanding	Neural computing Ability to process and interpret heterogenous information Spectral analysis	Machine learning used for Earth science mission and for terrestrial applications (e.g., agriculture, retail, etc.)	Codification of domain expertise in algorithms that allow for more rapid analyses and interpretation measurements to guide future actions. Stating mission goals in advance in a manner that an autonomous system can evaluate, rather than specific numerical goals for specific measurements.	Ability to assess whether overarching goals are achieved and to rapidly respond rapidly to unexpected occurrences
Descent and Landing (1 km – 0 m)	Multi-modal data fusion	Fusion of inertial, star tracking and sun sensing data to estimate attitude. Radar or lidar to estimate altimetry for touch-and-go maneuvers.	Autonomous fusion of high-density Lidar scans with descent imagery. Real-time shape-model refinement during descent.	Efficient storage and manipulation of large data sets Computing and memory	3D mapping for autonomous vehicles Visual/inertial fusion and 3D mapping from aerial platforms	Computationally efficient algorithms for multi-sensor modality data fusion Mathematical techniques for managing uncertainty Robustness to varying topographies and lighting conditions	Robustness to variations Computation efficiency to act in time (i.e., real-time)
Descent and Landing (1 km – 0 m)	Surface hazard assessment for landing	Extensive remote monitoring to manually identify any landing hazards.	Autonomous evaluation of rough topography in non-uniform gravity model for safe-landing zones that are within controllability of the spacecraft	Wide-coverage sensors with high resolution to detect hazardous terrains pre-landing Low-mass sensors Computing	NASA's Autonomous Landing Hazard Avoidance Technology (ALHAT) (JSC/JPL) [5]	Fast and small moving objects that require detection at remote distances. Completeness: ability to detect all hazards	Can we detect all hazards autonomously in such extreme environment?

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Small Body vicinity hazard detecting and tracking for close approach and landing	Ground-based processing analysis of images of landing site. Manual assessment of hazards and identification for safe maneuvers.	Autonomous detection of orbital debris, and outgassed/ejected material. Real-time refinement of surface model and hazard map.	Advanced computing	Image-processing techniques for change detection Autonomous vehicle industry tracking of multiple objects surrounding a vehicle	Extraction of accurate-enough motion models. Building dynamic trajectory models from limited observations	Ability to detect and predict dynamic hazards
	Spacecraft guidance and control near body	Ground-based radiometric and optical navigation based on landmarks. Well-orchestrated maneuvers for getting close to the surface (e.g., landing or touch-and-go). Only final 10s of meters executed autonomously	Fully autonomous descent, landing, touch-and-go, and return to "home" position. Ability to redirect or abort in response to detected hazards and anomalies.	Advanced computing Algorithms to estimate body motion Controlled maneuvering (precise and efficient thrusters)	NASA/JPL internal Research and Technology Development Program funding in proximity operations	Non-convex optimization for guidance Algorithm and computational complexity Controllability of the spacecraft (maneuvering)	Ability to react to dynamic hazards in real-time
	Multi-objective landing-site selection (value and safety)	Landing site selection requires months of mapping and deliberation from ground control.	Autonomous generation of risk/value surface maps. Algorithms for selecting safe and valuable landing sites to meeting mission objectives	Hazard assessment for landing	NASA's ALHAT program	Ability to assess value of sites remotely. Ability to weigh multiple, potentially competing objectives Derive metrics for landing site "value" based on high-level science goals.	
Surface Operations (0 m)	Target selection/ refinement from surface	Ground-based expert-driven surface target selection to be reached by surface assets	Target value assessment	Multi-sensor data fusion and autonomous spectral data analysis	Machine learning for spectral images (JPL/Ames Research Center)	Co-registration of composition data acquired during approach with data acquired on the surface	Forgiving: consequence of a false positive or false negative is not grave
	Multi-vantage point mapping	Ground-based mapping with some manual intervention for co-registration of orbital and surface asset-based imagery	Onboard mapping of data at various scale and from various vantage points	Advanced computing and large storage	Autonomous vehicles mapping	Mapping from low-vantage point of being on the surface of the body Managing heterogeneous uncertainty in the data	
	Change detection	Detection of dynamic events such as plumes [6] and Mars' dust devils [7]		Image processing and machine learning for visual detection	Visual inspection in medical field	Identifying subtle changes Signal to noise ratios	Mature technology exists

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Estimation of surface physical properties	Image-based terrain classification on Mars rovers. Wheel-slip estimation and adaptive control on Mars rovers (MSL). Ground-based post-impact estimation of coarse surface parameters by humans (e.g., coefficient of restitution from Philae lander bounce). Ground-based inference of surface properties from geological features (e.g., rocks and craters)	Onboard modeling of regolith dynamics and granular media in microgravity. Estimation of surface properties from remote observations. Estimation of surface terra-mechanical properties from brief, dynamic contact. Measurement and estimation of surface electrostatics.	Terra-mechanical models Particle-based terra-mechanical simulations. Experimental test beds for regolith contact dynamics in reduced gravity.	Academic research in terra-mechanics Army research in mobility impacted by terra-mechanics. Limited characterization of detailed surface properties from prior missions. NASA project for terrain classification based on thermal inertia.	Models are largely empirical Models limited to homogeneous terrains. Interactions with the surface in microgravity are typically brief/transient.	Complex dynamics but lower fidelity may be required for mobility
	Target selection/ refinement from surface	Surface hazards for touch-and-go maneuvers only assessed from distant imagery. Hazard assessment for Mars rovers, but in more benign terrains	Traversability and hazard models for surface mobility. Visual hazard detection from near-surface vantage point	Miniaturized high-quality visual inertial sensors. Advanced onboard computing.	NASA's Small Body autonomous surface navigation [8]	Hazard assessment is a function of the capability of the surface asset. Extreme terrain topography and platform design redefine what hazards would be	Can all hazards be detected autonomously to avoid premature mission ending?
Surface Operations (0 m)	Surface pose estimation and localization	Mars rovers visual inertial estimation. Secondary landers (Philae, MIcro-Nano Experimental Robot Vehicle for Asteroid [MINERVA], Mobile Asteroid Surface Scout [MASCOT]) have all relied on mother spacecraft for localization.	Surface attitude determination and self-righting. Vision-based localization during ballistic hops and on surface. Real-time map refinement Localization/navigation in shadowed regions.	Miniaturized high-quality visual inertial sensors (e.g., cameras and Lidars) Dust-shedding technologies Advanced onboard computing.	SLAM techniques from robotics domain (surface vehicles and drones) Terrain-relative navigation and guidance for small body touch-and-go maneuvers.	Visually challenging environment with rapidly changing illumination and scale during hops Dust/plume lens contamination. Lander may settle in surface concavities that occlude far-field visibility and communication. Mobility asset rotation/tumbling on surface that may result from low-gravity environments.	

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Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Surface motion planning	Mars rovers motion planning. Highly orchestrated and constrained (one-dimensional ascent/descent) touch-and-go maneuver trajectories.	Complex motion trajectories for heterogenous surface assets (e.g., hopping/ tumbling). Reasoning and risk and value and decision-making. Planning information-gathering actions to reduce uncertainty (e.g., hop up to map local area or "poke" surface to probe mechanical properties). Adaptive methods for planning with model refinement.	Advanced onboard computing. Ruggedized microgravity surface mobility platforms. Sensing and state estimation on surfaces of Small Bodies.	Mars Technology Program (2001-2007). NASA Innovative Advanced Concepts (NIAC) projects on Small Body autonomous surface navigation [9]	Extreme-terrain topography with non-traditional surface mobility platforms. Navigating in a complex and uncertain gravity environment. Possibility of "escaping" the body or getting "stuck" in a crack or deep regolith.	Complex and dynamic interaction between surface assets require in situ information to make informed and timely decisions
	Surface Mobility and control	Conventional TAG maneuvers are highly staged and quickly return to "home" orbit. Short, random hopping demonstrated with small secondary landers via internal actuation (MINERVA and MASCOT)	Targeted mobility to multiple destinations. Control of hopping, tumbling, and impacting on small bodies. Dust mitigation strategies.	Terramechanics models and simulations of regolith in microgravity. Experimental test beds for regolith contact dynamics in reduced gravity. Surface localization and pose estimation.	Spacecraft/Rover Hybrids (Hedgehog) NIAC project. JPL's "Limbed Excursion Mechanical Utility Robots (LEMUR)" climbing robot Applied Physics Laboratory's (APL) NASA-funded "POGO" project for Asteroid Redirect Mission (ARM) mission.	Highly irregular and granular surfaces with unknown shapes and physical properties. Dynamics in microgravity make it difficult to control surface contact forces.	
	Surface sampling and handling	Short-duration sampling during TAG with mechanisms such as brush drums and gas jets	Coring to preserve stratigraphy. Measuring sample quantity	Autonomous scooping, drilling, or other sampling technologies	Mars, Venus and other planetary mission sampling techniques. Bi-blade sampler at JPL	Very low pre-loading for sampling hard material	
Below Surface	Anchoring	Philae attempted anchoring with drills and harpoons, but both failed.	Ballistic anchoring (e.g., harpoons) or gentle anchoring (e.g., drills, hammer penetrators) strategies Resisting contact forces to remain grounded.	Grasping, grappling, straddling	ARM-mission techniques for grasping: gripping using micro-spines.	A priori unknown and highly variable terrain properties. Small forces can induce ballistic motion away from surface	

Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
	Large-object manipulation	ARM-mission studies and terrestrial prototypes. No flown missions.	Grasping/grappling techniques for large boulders. Spacecraft control with heavy distal payload	Lightweight, high-strength space robotic manipulators	Mining-industry autonomous extraction (horizontal mining). ARM-mission techniques for grasping: micro-spine gripper.	Uncertainty associated with interacting with terrain (including friability and material strength). Small forces can induce ballistic motion away from surface	
	Deep surface access (> 2 m)	Terrestrial drilling for oil and gas. No relevant missions or demonstrations	Drilling in microgravity regolith and rock.	Deep drilling Burrowing Insight's HP3 instrument	Honeybee drilling		
	ISRU	No relevant missions or demonstrations	Devices and strategies for excavating large volumes of material. Targeting surface regions with dense resource concentration	Terramechanics models and simulations for regolith in microgravity.	NASA ISRU (JSC)	Energy management. Resources sparsely distributed.	
	Architecture for Autonomous Systems	Custom architecture for each mission; sequence-driven missions	Goal-based, system-level autonomy for end-to-end missions	Software architectures Programming languages	Several products appear on market, but have had limited adoption. In robotics, the Robotics Operating System (ROS) for Open Source Foundation	Heterogeneous space platforms (cruise craft, surface assets, sub-surface assets). Limited market for deep-space applications	

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Table 4: Assessment of technologies needed for near-term DRM 1

Phase	Technology	State of the Art	Technology Gaps	Supporting Technologies	Relevant Research and Development (R&D) Projects (NASA, industry, academia)	Challenges and Risks	Key Points and Questions
All Phases	Monitoring and management of spacecraft health	Fault protection on spacecraft (disabled during critical events). Model and data driven techniques (Beacon-based Exception Analysis for Multimissions [BEAM]/ Spacecraft Health Inference Engine [SHINE] [13], Model-based off-nominal state isolation and detection (MONSID) [14])	Fault detection, isolation and recovery for increasingly complex systems	Fault detection, isolation, and recovery (FDIR) technologies Big-data trend identifications Instrumentation of devices and component technologies	Industrial efforts in trend identification for knowledge management companies (Amazon, Google, Facebook) Migration of industries to IoT (e.g., General Electric's instrumentation of flight engines) Aeronautics (NASA, U.S. Air Force, commercial) have technology that could be ported.	Fault identification and isolation Completeness and robustness of diagnosis Prognosis	
	Management and coordination of multiple assets on ground or in space at centralized platform to survey, monitor, characterize and identify targets	Dual spacecraft coordination – Gravity Recovery and Climate Experiment (GRACE) and Gravity Recovery and Interior Laboratory (GRAIL) missions, Mars surface assets and orbits	Multi-asset information sharing, model building, reasoning and decision making. Task negotiation/assignment of functions to spacecraft with distinct specific limited capabilities for a particular scientific or exploration problem.	Communication-based techniques for multi-asset localization	Multi-asset and multi-platform research. Mother daughter co-registration. Orbital surface localization for Mars rovers	Co-registration of approach composition data with surface acquired data Task assignment/negotiation among assets to achieve a function based on capability	
	V&V	V&V limited to well-defined and limited autonomous functions that operate within specific constraints	Techniques that would generalize and scale to more complex systems and scenarios	Mathematical tools for V&V	Testing-based programs for autonomous vehicles. Limited efforts under R&D program at NASA.	Generalization of the approaches and their scalability	Field in infancy and requires substantial development

In summary, the aforementioned technologies would need to be developed, adapted, matured, and tested to achieve DRM 1. There is a further level of specificity for each of these technologies that would be detailed as the mission concept is further fleshed out. Some capabilities such as perception-rich situational awareness and operating on the surface of an unknown environment would generalize to other DRMs, but a well-defined application would be needed to drive the development and evaluation of progress for advancing and achieving autonomy and assessing broader impact.

Part IV: FIndings

The Small Bodies DRM team finds the following actions and activities would enable the DRM scenarios described above.

Consider include engaging industry more effectively:

- Define crisp engineering challenges to present to industry to attract partnerships
- Scour DoD activities that have government rights and offer them to the proposing science community
- Assess applicability of automotive computing, sensing, and reliability standards and capabilities for human-rated AVs to potentially facilitate interoperability of relevant components: sensing, computation, software, etc.

Investments in autonomy for Small Body missions will provide far-reaching benefits. Implementing autonomy for Small Bodies will provide a “playground” for researching, developing, testing, and maturing technologies that can be used in more complex and more expensive mission scenarios. Small Bodies are accessible, diverse, and plentiful. Small Body research embodies challenges that are common to several other DRMs:

- Unknown topography for body mapping
- Extremely rugged surfaces (Europa, Enceladus)
- Dynamic interaction between assets and the environment (Venus, Titan, liquid bodies, etc.)
- A priori unknown surface properties

In addition, Small Body missions have certain advantages that would enable technology development:

- Lower cost for approach and landing
- More forgiving (impact with surface less harmful)
- Accessible via small spacecraft (SmallSats)
- Offer mission of opportunity (flybys of interstellar visitors)

Part V: Team and Contributors

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Part VI: References

[1] https://ieeexplore.ieee.org/document/7500757

[2] Bernard, D., Doyle, R., Riedel, E., Rouquette, N., Wyatt, J., Lowry, M., & Nayak, P. (1999). Autonomy and software technology on NASA's Deep Space One. *IEEE Intelligent Systems and their Applications*, *14*(3), 10-15.

[3] Jorda, L., Gaskell, R., Capanna, C., Hviid, S., Lamy, P., Ďurech, J., ... & Keihm, S. J. (2016). The global shape, density and rotation of Comet 67P/Churyumov-Gerasimenko from preperihelion Rosetta/OSIRIS observations. *Icarus*, *277*, 257-278.

[4] Preusker, F., Scholten, F., Matz, K. D., Roatsch, T., Hviid, S. F., Mottola, S., ... & Vincent, J. B. (2017). The global meter-level shape model of comet 67P/Churyumov-Gerasimenko. *Astronomy & Astrophysics*, *607*, L1.

[5] Epp, C. D., & Smith, T. B. (2007, March). Autonomous precision landing and hazard detection and avoidance technology (ALHAT). In *2007 IEEE Aerospace Conference* (pp. 1-7). IEEE.

[6] Thompson, D. R., Bunte, M., Castano, R., Chien, S., & Greeley, R. (2012). Image processing onboard spacecraft for autonomous plume detection. *Planetary and Space Science*, *62*(1), 153-159.

[7] Castano, A., Fukunaga, A., Biesiadecki, J., Neakrase, L., Whelley, P., Greeley, R., ... & Chien, S. (2008). Automatic detection of dust devils and clouds on Mars. *Machine Vision and Applications*, *19*(5-6), 467-482.

[8] Bhaskaran, S., Nandi, S., Broschart, S., Wallace, M., Cangahuala, L. A., & Olson, C. (2011). Small body landings using autonomous onboard optical navigation. *The Journal of the Astronautical Sciences*, *58*(3), 409-427.

[9] Hockman, B., & Pavone, M. (2017). Stochastic motion planning for hopping rovers on small solar system bodies. In *Proceedings of ISRR*.

[10] Mission Analysis, Operations, and Navigation Toolkit Environment. https://montepy.jpl.nasa.gov/

[11] Gaskell, R.W., "Characterizing and navigating small bodies with imaging data," *Journal of Meteoritics and Planetary Science,* June 2008, vol. 43 Issue: 6, pp. 1049-1061

[12] Reid, I.D., Davison, A.J., Stasse, O., Molton, N.D., "MonoSLAM: Real-Time Single Camera SLAM," in Transaction of Pattern Analysis and Machine Intelligence, June 2007, pp. 1052-1067, vol. 29

[13] James, M.L., Zima, H.P., "An introspection framework for fault tolerance in support of autonomous space systems", IEEE Aerospace Conference, 2008

[14] Kolcio, K, Fesq, L., "Model-based off-nominal state isolation and detection system for autonomous fault management," 2016 IEEE Aerospace Conference, 2016

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

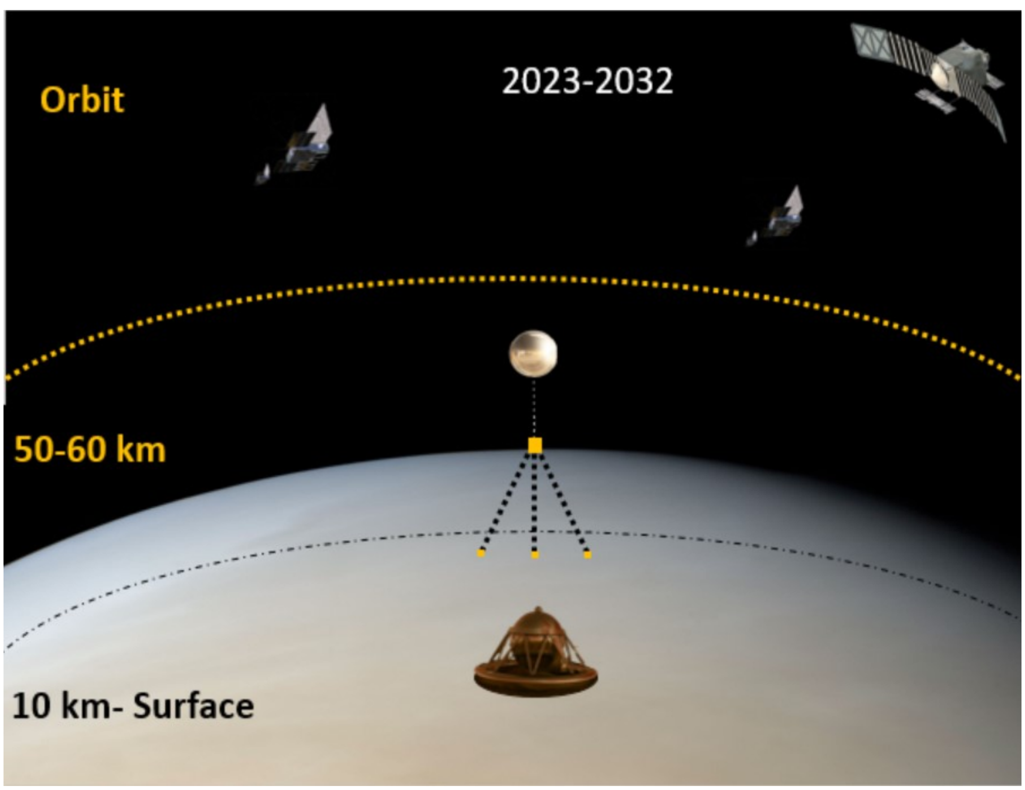

Figure 2. DRM 1 Concept Overview

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.

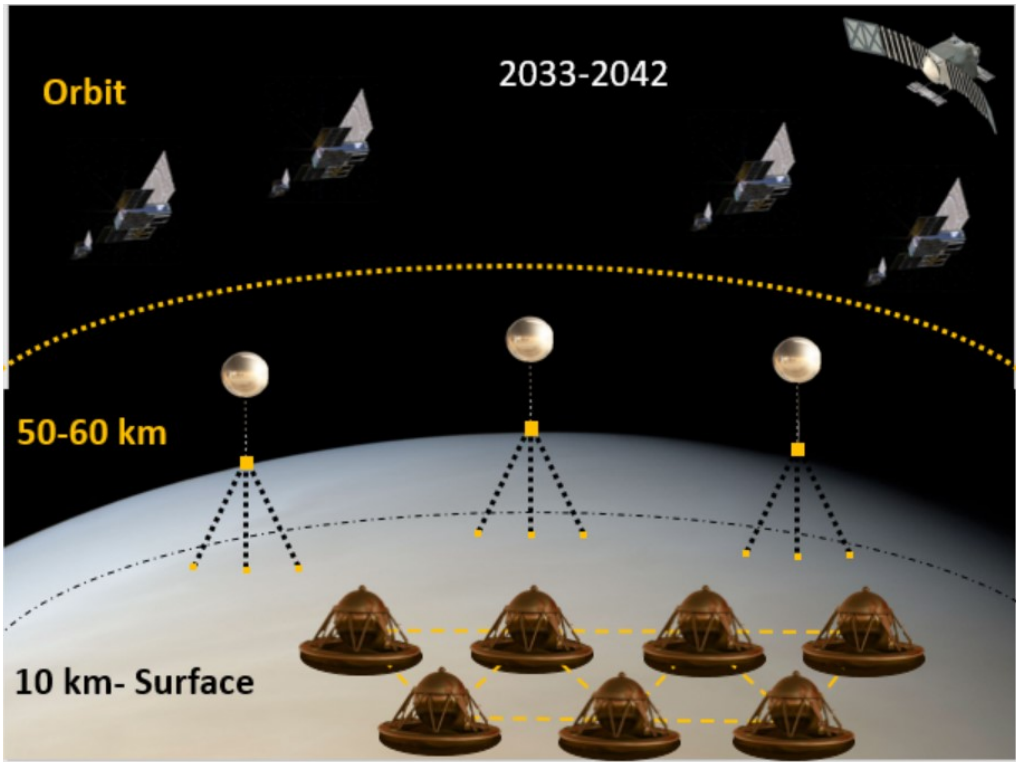

Figure 3: DRM 2 Concept Overview

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

The Venus Design Reference Mission team is comprised of:
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Part VI: References

1. https://nssdc.gsfc.nasa.gov/planetary/chronology_venus.html
2. Venus Flagship Mission website
   https://vfm.jpl.nasa.gov/venusdesignreferencemission/
3. Venus Flagship Mission, Final Report of the Venus Science and Technology Definition Team, Jeffery Hall et l, April 2009,
   https://vfm.jpl.nasa.gov/files/Venus+Flagship+Mission+Study+090501-compressed.pdf
4. Venus Climate Mission, David Grinspoon et. al., 2010
   https://solarsystem.nasa.gov/studies/202/venus-climate-mission/
5. A4. Venus Mobile Explorer, Lori Glaze et. al., 2010
   https://solarsystem.nasa.gov/studies/200/venus-mobile-explorer/
6. Venera D: Expanding our Horizon of Terrestrial Planet Climate and Geology through the Comprehensive Exploration of Venus, Report of the Venera D Joint Science Definition Team, David Senke and Ludmilla Zasova et al, Jan 2017
   https://www.lpi.usra.edu/vexag/reports/Venera-D-STDT013117.pdf
7. LLISSE: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180000692.pdf
8. Venus Aerial Platforms:
   https://www.colorado.edu/event/ippw2018/sites/default/files/attached-files/innersys_2_cutts_presid617_presslides_docid1136.pdf
9. Venus Aerial Platform Study
   https://www.lpi.usra.edu/vexag/reports/Venus_Aerial_Platforms_Final_Report_Summary_Report_10_25_2018.pdf
10. Planetary aero-vehicles:
    https://www.colorado.edu/event/ippw2018/sites/default/files/attached-files/innersys_2_cutts_presid617_presslides_docid1136.pdf
11. Aerial Platform Options for Venus, Jeffery L. Hall et al
    https://www.colorado.edu/event/ippw2018/sites/default/files/attached-files/innersys_3_hall_presid559_presslides_docid1028.pdf
12. Planetary aero-vehicles: https://link.springer.com/article/10.1007/BF00710794
13. Balloon Borne Infrasound as a Remote Sensing Tool For Venus, Siddharth Krishnamoorthy et al:
    https://www.colorado.edu/event/ippw2018/sites/default/files/attached-files/innersys_4_krishnamoorthy_presid493_presslides_docid894.pdf

14. Chien, S.; and Wagstaff, K. L. Robotic Space Exploration Agents. Science Robotics. June 2017.

15. Francis, R.; Estlin, T.; Doran, G.; Johnstone, S.; Gaines, D.; Verma, V.; Burl, M.; Frydenvang, J.; Montaño, S.; Wiens, R. C.; Schaffer, S.; Gasnault, O.; DeFlores, L.; Blaney, D.; and Bornstein, B. AEGIS Autonomous Targeting for ChemCam on Mars Science Laboratory: Deployment and Results of Initial Science Team Use. Science Robotics. June 2017.

16. Chien, S.; Sherwood, R.; Tran, D.; Cichy, B.; Rabideau, G.; Castano, R.; Davies, A.; Mandl, D.; Frye, S.; Trout, B.; Shulman, S.; and Boyer, D. Using Autonomy Flight Software to Improve Science Return on Earth Observing One. Journal of Aerospace Computing, Information, and Communication (JACIC),196-216. April 2005.

17. Doubleday, J.; Chien, S.; Lou, Y.; Clark, D.; and Muellerschoen, R. Onboard Autonomous Response for UAVSAR as a Demonstration Platform for Future Space-Based Radar Missions. Acta Futura, 9: 31-39. 2014.

18. Hayden, D.; Chien, S.; Thompson, D.; and Castano, R. Using Clustering and Metric Learning to Improve Science Return of Remote Sensed Imagery. ACM Transactions on Intelligent Systems Technology, Special Issue on AI in Space, 3 (3). May 2012.

19. Rabideau, G.; and Benowitz, E. Prototyping an Onboard Scheduler for the Mars 2020 Rover. In International Workshop on Planning and Scheduling for Space (IWPSS 2017), Pittsburgh, PA, June 2017.

20. Chi, W.; Chien, S.; Agrawal, J.; Rabideau, G.; Benowitz, E.; Gaines, D.; Fosse, E.; Kuhn, S.; and Biehl, J. Embedding a Scheduler in Execution for a Planetary Rover. In International Conference on Automated Planning and Scheduling (ICAPS 2018), Delft, the Netherlands, June 2018.

21. A. I. Mourikis, N. Trawny, S. I. Roumeliotis, A. E. Johnson, A. Ansar, L. Matthies , “Vision-aided inertial navigation for spacecraft entry, descent, and landing”, IEEE Transactions on Robotics, vol 25, no 2, April 2009

22. A. Ansar, L. Matthies, "Multi-modal image registration for localization in Titan's atmosphere", IEEE/RSJ International Conference on Intelligent Robots and Systems, October 2009

23. J. Cutts, D. C. Nunes, K. L. Mitchell, D. A. Senske, M. T. Pauken, L. Matthies, P. Tokumaru, "Exploration targets for a mission concept with multiple Venus gliders", Workshop on Venus Exploration Targets, May 2014

24. P. T. Tokumaru, J. Balaram, J. A. Cutts, L. Matthies, "Fixed and rotary wing flight of small air vehicles on Mars, Venus, and Titan", 11th International Planetary Probe Workshop, June 2014

25. L. Matthies, J. Cutts, P. Tokumaru, M. Pauken, "Venus guided aerosonde (VGA) for

landing site reconnaissance", 11th International Planetary Probe Workshop, June 2014

26. Jonathan Grandidier , Alexander P. Kirk, Mark L. Osowski, Pawan K. Gogna, Shizhao Fan, Minjoo L. Lee, Margaret A. Stevens, Phillip Jahelka , Giulia Tagliabue , Harry A. Atwater, and James A. Cutts, "Low-Intensity High-Temperature (LIHT) Solar Cells for Venus, Atmosphere", IEEE Journal of Photovoltaics, Vol. 8, No. 6, pp. 1621-1626 November 2018
27. Philip G. Neudeck, David J. Spry, Michael J. Krasowski, Norman F. Prokop, Glenn M. Beheim, Liang-Yu Chen, and Carl W. Chang, "Yearlong 500 C Operational Demonstration of Up-Scaled 4H-SiC JFET Integrated Circuits", Journal of Microelectronics and Electronic Packaging, vol. 15, no. 4, pp. 163-170 ©IMAPS
28. K. Fu, H. Fu, X. Huang, T. H. Yang, H. Chen, I. Baranowski, J. Montes, C. Yang, J. Zhou, and Y. Zhao, "Threshold switching and memory behaviors of epitaxially regrown GaN-on-GaN vertical p-n diodes with high temperature stability", IEEE Electron Device Lett., vol. 40, 375 (2019).
29. X. Huang, R. Fang, C. Yang, K. Fu, H. Fu, H. Chen, T. H. Yang, J. Zhou, J. Montes, M. Kozicki, H. Barnaby, B. Zhang, and Y. Zhao, "Steep-slope AlGaN/GaN HEMT with oxide based threshold switching device", Nanotechnology, vol. 30, 215201 (2019).

DRM TEAM SUMMARY REPORTS

Astrophysics Design Reference Mission Report Summary

In the Exoplanet Science Strategy Report[25], the National Academies recommend that "NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars." For direct imaging of exoplanets, the size of the telescope aperture is directly correlated with the probability of finding Earth-like exoplanets—the bigger the aperture, the better the probability. In other areas of astrophysics, larger aperture has direct correlation to better science, as well. Past experiences have shown that developing a large observatory to fit—even when folded—into a single launch fairing of an existing or a future planned launch vehicle involves various technological, programmatic, schedule, and cost challenges. Is there a way to mitigate these challenges and improve the cost and risk postures of future observatory implementations? Furthermore, servicing these observatories in space to extend their lifetimes and update instruments to provide many decades of scientific returns is also challenging. The world has both marveled at and profited by the benefits of Hubble Space Telescope (HST) servicing. How will NASA ensure future observatories have similar opportunities to be serviced? To address

[25] National Academies of Sciences, Engineering, and Medicine. *Exoplanet Science Strategy*. Washington, DC: The National Academies Press. [https://doi.org/10.17226/25187] 2018.

these issues, NASA and other government entities are expressing growing interest in exploring the value proposition of in-space robotic assembly and servicing for large space assets including optical telescopes. This interest is also reciprocated by industry through internal investments and public-private partnerships.

The Astrophysics DRM team explored the role of autonomy in enabling robotic assembly of an optical telescope in cislunar space with delivery, operations, and servicing at the Sun-Earth Lagrange Point (SE-L2). Onboard autonomy with minimal human supervision plays a central role in this DRM scenario. While NASA has experience with in-space assembly via astronauts or high-bandwidth, human-in-the-loop telerobotics, the following concerns, among others, make autonomous operations—with minimal human supervision via telemetry—a key enabling feature:

- The time delay due to orbit location (Sun-Earth–L2 and Earth-Moon–L2)
- The large state-space of variables that must be tracked and reasoned over during assembly
- The deliberate contact-based assembly and in situ verification and validation needed
- The dimensions and inertias of the modules
- The multiple concurrent blind mates that are needed for assembly
- The sensitivity to disturbances and contamination of the assemblage
- The overall mission cost and risk posture

The Astrophysics DRM team suggests the following autonomous DRM scenario.

DRM Scenario: In-space Assembly of Large Telescopes

The overall reference mission concept is as follows. A 20-m, filled-aperture, segmented, non-cryogenic ultraviolet/visible/near-infrared observatory will be assembled from its modular components in cislunar orbit using autonomous robotics. The mission will use multiple launches for the modules. The observatory instruments will be updated in the operational environment, i.e., SE-L2. Mission components include the observatory spacecraft, robotic systems for assembly and servicing, and cargo delivery vehicles (that bring the modules to the assemblage) that will work together to assemble and service the observatory.
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:

Autonomous Onboard System Management: In-space assembly and servicing will require planning to coordinate many different agents (e.g., spacecraft, robots, delivery vehicles), manage resources and environmental effects, and ensure system level performance by sequencing and monitoring many different functional-level autonomous behaviors. This capability is an enabling feature.

Autonomous Maneuvers, Mobility, and Manipulation: The complement of system-level management is management of the many different functional-level autonomous behaviors needed to assemble and service the observatory. Robotic systems have to autonomously "go where needed" and "manipulate what is needed." Autonomous orbital maneuvers for spacecraft berthing and attitude control, autonomous robotic mobility over the assemblage to access different locations, and autonomous manipulation (including soft goods) to assemble different types of observatory modules are key enabling features. These contact-based behaviors have to be successfully executed, subject to a large state-space of variables that need to be monitored, tracked, or controlled.

Autonomous In-space Verification/Validation: Autonomy is needed to "check your work." An observatory assembly has strict requirements for precision of module placement, structural stability, and operational thermal control, etc. In addition to the precise assembly, the validation of assembly should be continual and enabled by incorporating different kinds of sensors and autonomous behaviors.

Autonomous Onboard Anomaly Detection: This mission scenario involves deliberate contact between autonomous agents and modules, some of which may have fragile components. It is critical that the system is robust and employs continuous and autonomous anomaly detection to ensure that the contact-based events are performed within the bounds of nominal behaviors. Furthermore, it is paramount that the system autonomously and gracefully transitions from different anomalous situations to safe states (i.e., safing) where engineers on the ground can intervene to recover. While autonomous recovery is an ultimate goal, autonomous detection and graceful safing is a key requirement.

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

- Systems engineering for autonomy
- Modular design principles for the observatory, particularly soft goods for sunshades
- Robotics-informed "joining" interfaces
- Perception sensors and metrology
- Computing, particularly for computer vision
- Modeling and simulation
- Non-destructive testing approaches

Findings

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

1. Fund a technology-gap analysis and technology roadmap activity with emphasis on identifying autonomy capabilities that may be leveraged from other space or terrestrial applications

2. Set up virtual and physical test beds in laboratory settings for technology development and risk reduction demonstrations with equal emphasis on system- and functional-level autonomy
3. Implement in-space demonstrations or risk-reduction efforts using small spacecraft or existing assets (e.g., inside and outside the ISS)

Earth Design Reference Mission Report Summary

Few Earth-observing satellites in operation today include instruments that can be used to observe a specific Earth location. Almost all of these missions are manually commanded, which requires several days of instrument command formulation and testing, followed by transmission of information to the platform mission operations center, followed by more testing and eventual upload of information to the satellite for further testing and confirmation.

Recently, the Earth Science community has experimented with operations of instruments located on different platforms at different vantage points in consort with one another. These experiments involve constellations of small satellites, aircraft, and in situ platforms. A key element of this capability is the autonomous control of instruments and aircraft trajectories. Each platform's vantage point has its own strengths and weaknesses, but these assets can be combined to execute new observing strategies. This work has revealed new opportunities for studying natural phenomena and physical processes that were not previously accessible from space. New research can be conducted that will increase our understanding of transient and transitional phenomena and of physical processes where the time constants involved require multiple observations in close proximity or where the necessary revisit rate is on the order of minutes to hours. These new observational capabilities also allow a more direct coupling with models, including the possibility of directing observations to update models, based on assessments of the quality of model output.

The Earth DRM team suggests the following DRM scenario to take advantage of this new paradigm.

DRM Scenario: A Model-driven Observing Strategy

This scenario describes an observing strategy for Earth science driven by models. This DRM scenario involves obtaining data from mission assets (including a constellation of small satellites and possibly airborne, ground-based, or in situ elements), learning from the data, and then making real-time decisions to command the assets to collect additional data to verify and further refine models to improve the quality of predictions. This model-based scenario would be useful for both operational forecasting and scientific research.

For operational forecasting, as the model runs, analysis identifies diminishing forecast quality in a location/region and determines the observational data that is needed to restore quality. An autonomous supervisory system then determines the most effective strategy (and contingencies) for collecting the needed data, and tasks the appropriate observation elements to collect and provide data. When the data are returned and assimilated, the model is updated and the model quality is reassessed to ensure the expected improvements have occurred.

To conduct scientific research into a process or phenomenon, this model-based approach involves running a repeating test/debug cycle on models to improve their ability to predict the behavior of physical processes and natural phenomena. The researchers identify a class of phenomena to be studied (e.g., F2 tornadoes) and start running the research model. The model then tasks the observing system to identify and make observations of the instances of that phenomenon as they occur. A researcher assesses the efficacy of the model and then defines an experiment or a campaign to collect more data, do analysis, adjust the model, and repeat the process.

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:

Select the Appropriate Asset: When the system indicates a model needs data, there may be several instruments and platforms available to provide that data and there may be constraints due to data quality or availability of the instruments. Autonomy would enable the system to select from multiple heterogeneous assets and task the optimal set of measurement capabilities.

Resolve Conflicts and Issue the Necessary Tasking without Human Intervention: Time scales for tasking are at the second- and minute-level and are likely to be substantially different each time they are needed. Human operators are unable to respond quickly enough and with low enough error to manually perform the optimization and subsequent tasking. There may be conflicting tasking from multiple sources (i.e., research and operational forecasting systems using the same observing assets) that would need to be prioritized based on goal-oriented mission re-planning strategies**.** Autonomy would allow the system to continuously re-task elements to accomplish mission goals without human intervention.

Monitor Workflow, Detect and Compensate for Faults: For an autonomous, model-driven observing system to operate reliably, it must monitor the health not only of the overall system, but also of the functional components, to effectively plan and assign tasks. In a complex interconnected system with many different demands, many pathways, and thousands of failure modes, continuous monitoring and autonomous decision making will be necessary to identify and mitigate faults. Autonomy would enable detection of faults and the execution of complex contingency plans to optimize system availability. Furthermore, autonomy would enable the system to monitor instrument performance and dynamically re-calibrate when necessary.

Verifying the Improved Forecast: Forecasts are complex representations of a non-linear, inhomogeneous, dynamic, natural system. Improvements to either research or operational models expected to result from observing system tasking must be validated to ensure the resulting forecast actually supplied the improvements expected. If expectations are not met, additional observations and/or processing may be required, and the changes incorporated into future mission operations. The autonomous observing system must assess these potential improvements to the model, alert the operators, and identify and direct additional corrective action. The system must also improve its own performance when shortcomings are identified. Autonomy would enable quick reaction and re-tasking if the results are not as expected for a complex set of observational assets.

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

- Onboard processing
- Adaptive computer security (multi-mission, threat response)
- Models capable of continuous operations and identifying regional degradations
- Assimilation models supporting irregular input
- Collision avoidance and collaboration with other assets (i.e., non-NASA)
- Autonomous mission evaluation, including testing, safety evaluation, threat detection
- Algorithms to support autonomous operations, including low-load algorithms (e.g., use of look-up tables instead of calculations) to detect desired observations
- System assessment using multiple and distributed logs from various sources with varying authority

For NASA's Earth Science Program, selecting an appropriate set of research and applied science domains in which to initiate such experiments is necessary. To date, research areas including Energy and Water Cycle (specifically, hydrology), Air Quality, and Cryosphere have indicated needs for model-driven observing capabilities. Since much of the autonomy required to support this model-based observing strategy requires the integration of emerging—but relatively mature—components, the use of a ground-based testbed would be a useful way to demonstrate the value of a model-driven observing system and to debug the integration of the individual components. When a working and conceptually useful system can be demonstrated on the ground, the next step would be to fly one of the sensing nodes on-orbit and demonstrate that the system as a whole would be useful and feasible. Then a full observing system could be developed with appropriate flight-mission components.

Findings

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

1. Develop a ground-based, multi-site, multi-party testbed to mature the technology integration and to enable development of integrable technologies.

2. Run experiments for each of the science communities that need a demonstration of the value of this type of observing strategy to show how autonomous operations can provide more and better data than the conventional approach.
3. Develop a theoretical basis for intercalibration among instruments to enable integrated and near real-time data consumption as input into the control system.
4. Develop computational forecast models of physical processes and natural phenomena that run continuously and in real time.
5. Further develop the airborne mission-management software to be used with models and in situ and on-orbit components, as well as airborne assets.
6. Develop a mission-operations concept in which the role of the humans is to oversee and potentially override the autonomous system. This implementation will involve a heavy human-factors analysis and evaluation, possibly similar to what is being done in NASA's Aeronautics Research Mission Directorate (ARMD) or the Human Exploration and Operations Mission Directorate (HEOMD).
7. Develop a fairly comprehensive autonomous model-based safety analysis capability so that all autonomous and manual decisions are evaluated as they are being formulated for safety (and collision) implications.
8. Develop an effective model-based computer security capability for protecting assets from rapidly evolving cybersecurity threats and for monitoring and assessing the state of NASA owned assets as well as those of other collaborators.

Heliophysics Design Reference Mission Report Summary

The current NASA Heliophysics System Observatory (HSO) has provided unprecedented coverage of the Sun and its impact on Earth, the planets, and other small bodies (e.g., comets) in the solar system. However, improved space weather predictions are critical to safeguard the nation's technological assets and ensure the safety of astronauts—whether they are in Earth orbit or en-route to/from the Moon or Mars—and is a prime motivator for this DRM. Improved space weather prediction requires missions that enable scientists to accomplish the following with high accuracy and confidence:

- Predict (not after the fact) whether a sunspot region will spawn coronal mass ejections (CMEs), solar flares, and energetic particle events in the next hours to days
- Predict the arrival time and physical properties of abrupt changes in the solar wind (including CMEs)
- Predict the geoeffectiveness (capability of causing geomagnetic disturbances) of CMEs, whether they are directed toward Earth or slightly away from Earth
- Provide an "all clear" prediction for inclement space weather activity over the next month

Furthermore, from just after the beginning of the Space Age and the establishment of NASA, a mission to the Local Interstellar Medium (LISM) has been under discussion. The remarkable science opportunities that arise from such an "Interstellar Probe" traveling beyond the Sun's sphere of influence have fueled the community for almost six decades, resulting in multiple international study efforts. Most recently, NASA funded a study of the "Pragmatic Interstellar Probe,"[26] which would use available/near-term technology launch vehicles and kick stages to reach asymptotic speeds at least three times that of Voyager 1, which is currently the fastest spacecraft escaping the Sun's gravity well.

Historically, the science related to such a mission has been anchored in heliophysics, but in recent studies and workshops three compelling science goals have emerged that span heliophysics, planetary sciences, and astrophysics:

- Understand our heliosphere as a habitable astrosphere
- Understand the evolutionary history of the solar system
- Open the observational window to early galaxy and stellar formation

Autonomy technology would enable mission success; moreover, autonomous spacecraft and payload operation is the *only* way to execute these missions given the distance involved. The Heliophysics DRM team suggests two autonomous DRM scenarios.

DRM Scenario: An Autonomous Space Weather Constellation

This Autonomous Space Weather Constellation consists of a constellation of spacecraft in different orbits around the Sun offering a simultaneous $4\boldsymbol{\pi}$ steradian view of the solar surface. Its aim is filling the gaps in our observational capabilities to facilitate validated, near real-time, data-driven models of the Sun's global corona, heliosphere, and associated space weather effects.

Autonomy will enable space weather nowcasting and forecasting from a global-to-regional level that cannot be done today and will safeguard human exploration to the Moon and Mars.

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:

Onboard Decision Making to Effectively Utilize Resources (Power, Observing Capabilities, Onboard Storage, Telemetry): Autonomy will help maximize scientific/operational value for given telemetry. Observed regions deemed most important for accomplishing scientific and operational space weather objectives will be prioritized for transmission to mission ground

[26] McNutt, et al. *Interstellar Probe: Humanity's Journey to Interstellar Space*. [http://interstellarprobe.jhuapl.edu] 2019.

stations. This practice will provide the data needed for a continuously driven model of the Sun and heliosphere to improve space weather predictions.

Onboard Machine Learning (Inference) for Local Space Situation Awareness and to Provide Space Weather Alerts: Each probe in the constellation must be capable of preparing its own space weather report and broadcasting the report to the constellation. This practice should improve the constellation's global space weather awareness.

Provide Multi-vantage-Point Data Needed for a Continuously Driven Model of the Sun and Heliosphere: Autonomy will enable data collection from unprecedented vantage points and unexplored regions to help us understand the Sun-to-Earth connection. The integrated space weather model should autonomously decide which data sources will be used in updating the estimated state of the Sun and heliosphere, be able to evaluate the accuracy of its own predictions, and adaptively improve. To speed up the model's improvement, there should be a mechanism by which human feedback can be accepted (i.e., an active learning feedback loop).

Global Imagers Autonomously Identify 'Interesting' Regions, and Direct More Detailed Telescopes: To autonomously direct other resources, mission elements must possess space situational awareness in a global and local context.

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

- Small-spacecraft-based communication and propulsion.
- Space-qualified high-throughput processors.
- A testbed for simulating the constellation. Even though the testbed itself is not considered autonomy technology, it drives development of the aforementioned autonomous capabilities. A testbed is also needed to refine satellite/instrument requirements.

DRM Scenario: An Interstellar Probe

The interstellar probe will travel to the LISM and measure the environment beyond the solar system. The probe will travel at 20 AU/year for 50 years to reach 1000 AU. The probe will make comprehensive, state-of-the-art, in situ measurements of plasma and energetic particle composition, magnetic fields, plasma waves, ionic charge states, energetic neutrals, and dust that are required for understanding the nature of the outer heliosphere and exploring our local galactic environment. The interstellar probe will answer key questions about the evolutionary history of the solar system and provide key measurements pertaining to early galaxy and stellar formation.

As the interstellar probe transits outside our solar system, the spacecraft must rely on a "smart" autonomy system consisting of multiple spacecraft subsystems (e.g., to accomplish anomaly recovery) because telecommunication capabilities will be severely degraded. In addition, the payloads must have autonomous capabilities to take advantage of unexpected observations once the spacecraft is in a new, unexplored region while utilizing a limited data downlink for science measurements.

This DRM scenario requires a level of autonomy that is not currently available. In addition to the autonomy technology advancements required by the previously described DRM scenario (Space Weather Constellation), additional advancements in autonomy technology are required for this Interstellar Probe mission scenario to perform the following:

Autonomous Spacecraft Fault Detection and Correction: Autonomy is needed for spacecraft hardware and software fault detection and recovery. As the Interstellar Probe transits to the outer heliosphere and even beyond the solar system, the real-time commanding of both the spacecraft and payloads will be severely limited and not feasible due to the increased time required to transmit commands over increasingly long distances. Hence, it is essential that the spacecraft possess autonomous fault detection and correction capability because it will be on its own once it travels beyond the real-time commanding region.

Smart-instrument Data Collection: The science telemetry will be severely limited, hence a uniform data-collection strategy (i.e., constant rate) may not be the best observation plan, especially when the spacecraft transits some unforeseen interesting regions (e.g., heliopause). Therefore, the instrument must be “smart” enough to switch to a higher data rate once it detects an interesting region.

Onboard Feature Identification and Prioritization: Similar to the Space Weather Constellation DRM scenario, the Interstellar Probe mission will also require some type of onboard feature identification capability in conjunction with the smart-instrument data collection. Combination of the two advancements in autonomous technology will mitigate risk and enable the mission.

To enable autonomy in this Interstellar Probe scenario, advancements in the following supporting technology areas are required in addition to those listed for the Space Weather Constellation scenario:

- Advanced propulsion technology (long-lasting)
- Advanced communication technology to support long-distance communications
- Lightweight materials
- Compact instrumentation

Findings

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

1. Develop a space weather buoy demonstration mission to orbit the Moon and serve as a gateway space weather buoy
2. Develop a testbed to assess effectiveness and return on investment of various Space Weather Constellation configurations
3. Consider a *magnetohydrodynamics* modeling component as a key element of the mission
4. Develop spacecraft hardware and software fault detection and recovery
5. Develop compact “smart” instrumentation
6. Develop artificial intelligence/machine-learning techniques to facilitate onboard data processing and local space-situational awareness
7. Develop advanced observation modes and a smart downlink strategy for key measurements
8. Develop autonomous fault detection and mitigation technologies for the spacecraft subsystems
9. Require a path for flight demonstration for technologies such as computer accelerators as part of the technology readiness level (TRL) maturation

Mars Design Reference Mission Report Summary

NASA has studied Mars more than any other solar system object outside Earth and the Moon. The scientific exploration of Earth’s planetary neighbor has largely focused on addressing the presence and persistence of water, geochemistry, geology, and atmospheric evolution.

Prior, current, and near-term missions are filling in fundamental knowledge gaps regarding Mars and in doing so, support models of how the Mars system functions and has evolved. But these missions involve singular spacecraft in singular localities. A sustained, wide-area study is needed to enable astrobiological research concerning potential past, modern, and future (human) life on Mars, to support system-level understanding of Mars processes and conditions on a regional scale, and to support future human exploration.

Because of this need, the Mars team’s suggested DRM is not just a single mission but a practical, scalable, and sustainable Mars exploration campaign that establishes an exploration framework on Mars. In this framework, new spacecraft, new rovers, and missions themselves become new elements within the campaign’s framework. This campaign will study the groundwater ice in the context of climate and regional geology, local weather, and possible biology, while also providing detailed insight into the location and potential exploitation of subsurface water on Mars.

The Mars DRM team suggests the following DRM scenario.

DRM Scenario: A Mars Subsurface Geohydrology Investigation

This science-motivated investigation will consist of multiple missions to Mars to survey the planet on the scale required. Each mission will consist of several surface assets. The first mission will use a small number of assets with a target zone of tens of square kilometers. The number of assets will be scaled up for each mission in this scenario until sufficient assets are in place to meet the objectives and complete a detailed geohydrology map on the scale of the expected human exploration zone (~100-km radius).

The investigation scenario is not possible without substantial developments in autonomy. The sheer area to be investigated requires many agents—including a fleet of rovers, helicopters, a fixed lander, and an orbiter. Each asset cannot wait for an Earth-based team to provide daily instructions on where to move, which targets to select, and whether the target is of interest.

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:

Individual Agent Task Planning: Autonomy will allow an individual rover to inspect its surroundings, identify a target location to study, and determine if the science data is sufficient or if another target should be identified and analyzed.

Collaborative Multi-agent Task Planning: Autonomy will allow the individual agents to cooperate and efficiently implement a larger plan and automatically adjust the plan based on new data. For instance, the system must be capable of maintaining an overall map and selecting targets for each agent based on minimum movement or based on expectation of findings.

Sample Acquisition and Delivery: Autonomy will allow for automated sample collection and manipulation, including activities such as safely operating a drill, manipulating samples returned by the drill, and delivering the samples to the instruments on the same agent or on another agent.

Surface Navigation: Autonomy will allow each individual agent to traverse an area to a target specified by the mission plan. For example, the agent will determine the best route and avoid obstacles to reach the target using the optimum route based on risk, time, and energy.

Scientific Autonomy: Autonomy will provide the ability to analyze the science data in situ. The science instruments will need to adjust and tune themselves based on data obtained. Science instruments will also need to reduce data volume by identifying interesting data and culling uninteresting data. The instruments should also provide decisional information to the local rover and the larger network of assets to determine future targets.

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

- Surface imaging computing into the Digital Terrain and Geology Map (DTGM)
- High-performance remote computing power to support machine learning, including neural networks
- In situ, remote sensing of subsurface structure at rover scale for integration with DTGM for 3-D models
- An onboard interest operator to analyze, prioritize, and decide the next activity, especially for transient events
- Delay-tolerant networking (DTN) and mesh networking.
- Peer-to-peer interface standards for multiple interacting agents
- High bandwidth (on the order of 5Mbits/second), surface-to-surface, over-the-horizon data communications
- A lightweight drill capable of delivering potentially wet samples from minimum depth of 1-5m
- Ground-penetrating radar and magnetic induction spectroscopy tuned for water detection

Findings

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

1. Embrace the paradigm of the Mars Exploration Campaign with a scalable network of cooperating, independent assets.
2. Continue to develop autonomous navigation and operation skills, such as the ability to drill and handle samples. This technology cuts across almost any robotic planetary mission.
3. Develop artificial intelligence techniques for in situ science data analysis for each type of instrument expected to be deployed on Mars or other planetary missions.
4. Immediately start to develop very small, low-powered, peer-to-peer interface standards for multiple agents.
5. Develop high-bandwidth, peer-to-peer data communication devices.
6. Develop much more powerful spaceflight-compatible computing platforms. The base ship platform should be capable of performing the equivalent of "cloud computing" services for surface assets.
7. Develop artificial intelligence techniques to monitor health of surface assets and identify and work around faults to reduce risk and increase operational efficiency.

Moon Design Reference Mission Report Summary

The Moon is an ideal exploration target for humans and robotic explorers. The Moon is the cornerstone of planetary science and provides the foundation for our collective understanding of many planetary processes. Results of prior and ongoing missions have proved that the Moon is an attainable, interesting, and useful location to study—but also that there is still more to learn and explore.

The Moon is the most accessible target for resuming human exploration beyond low Earth orbit (LEO). The Moon's vast and accessible resources make it a critical enabling asset for any United States' activities beyond LEO. Future surface missions to the Moon will provide NASA with much-needed ground truth for orbital datasets, as well as increase capabilities for automation that will enhance future missions and enable exploration of extreme environments.

The Lunar Exploration Analysis Group (LEAG)—a community-based, interdisciplinary forum that NASA formed to provide input and guidance regarding Agency lunar exploration objectives—identified three themes that address Agency goals for future lunar exploration:

1. **Science**: Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them.
2. **Feed Forward**: Use the Moon to prepare for future missions to Mars and other destinations.
3. **Sustainability**: Extend sustained human presence to the Moon to enable eventual settlement.

The Moon DRM team suggests three autonomous DRM scenarios with general applicability to a variety of lunar exploration scenarios.

DRM Scenario: Lunar Roving Explorer (A Long-duration, High-speed Rover)

The long-lived, high-speed rover is a surface-exploration mission designed to investigate hundreds of scientific sites over a 1000-km traverse during two Earth years. The goal of this mission is to use autonomous mobility to acquire scientific measurements over a diverse array of lunar geologic terrains, addressing many key Decadal Survey[27] and Lunar Exploration Roadmap[28] objectives.

DRM Scenario: Orbital Polar Resource Explorers

This mission archetype uses coordinated, small, distributed spacecraft to fly as low as possible (10-20 km) above the surface and survey potential lunar surface volatile deposits from orbit to provide preliminary scouting of resource sites.

DRM Scenario: Sub-lunarean Void Explorer

This mission archetype explores a sub-lunarean void autonomously, without user guidance; assesses the utility of the sub-lunarean environments for human habitation and shelter; and increases understanding of the history of mare volcanism. Both propulsive robotic spacecraft and advanced mobility systems are proposed.
These three DRM scenarios all require of autonomy that is not currently available. Advancements in autonomy technology are required for these mission scenarios to perform the following:

Autonomous Local Navigation: To enable this capability, the rover will have to collect measurements while in motion with remote-sensing systems (e.g., Light Detection and Ranging [LiDAR] and/or stereo cameras). The information gathered will be processed onboard to build a model of the surrounding environment. From the model, potential hazards will be identified and an optimal traverse path will be computed without interaction of human controllers or computational resources on Earth.

Adaptation: Adaptive autonomy builds on the autonomous navigation outlined above but enables a human monitor to adjust a traverse or measurement objectives based on new observations. This technology will enhance the capability and science return.

Coordination of Multiple Robots/Assets: If a large number of surface assets have a mobility component, it will not be possible to control and monitor them individually using the standard operation methods presently used for planetary rovers, particularly if interactions with human

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[27] National Research Council Committee on the Planetary Science Decadal Survey. (2011). *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, D.C.: The National Academies Press. [http://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022].

[28] Lunar Exploration Analysis Group. (2011). *The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities*. [http://www.lpi.usra.edu/leag/LER-Version-1-1.pdf].

explorers are desired. Therefore, the network of assets will need to communicate and coordinate with each other autonomously to identify the objectives of each and ensure productive non-interference.

Planning and Coordination of Multi-robot and Human-robot Teams: Future human missions may use mobile robotic assets to help collect measurements and complete maintenance tasks around a lunar field station. As lunar in situ resource utilization technologies are developed and implemented, planning and coordination of multi-robot and human-robot teams will be required.

To enable autonomy in these DRM scenarios, advancements in the following supporting technology areas are required:

- LiDAR
- Stereo imaging and processing
- Cross-link communications
- Cooperative power sharing/distribution (wired, inductive, or beamed power transfer)
- High-capacity computing power capable of advanced onboard processing and modeling
- Machine-learning platforms/architectures
- Team-level localization
- Scheduling/planning in high-dimensional state spaces, with uncertain observations of environment and human performance, team actions, and shared beliefs
- Inertial Measurement Units (IMUs)

Investment in autonomous navigation can not only enhance and enable a long-lived rover like the Lunar Roving Explorer discussed above but can also feed into the design of other missions that incorporate mobility. By identifying hazards and optimal traverse paths, the asset can overcome obstacles without the need for human interaction. As exploration proceeds further into the solar system, communication time increases, and human involvement can substantially hamper progress; in some extreme environments, the wait can even put the mission at risk. Additionally, the inclusion of autonomy in almost any form will increase the processing requirements of the onboard computer. It is essential that NASA test and develop new processors that can handle the increased load. This development should be carried out at various scales so that capable processors will be available for power-limited environments such as those encountered on small spacecraft as well as in more resource-rich environments.

Findings

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

1. Establish study teams to investigate the current use of autonomous navigation and hazard avoidance

   a. Leverage recent industry advances in autonomous navigation
   b. Assess current TRL levels and identify shortcomings
2. Establish requirements for onboard analysis capabilities for conducting autonomy
   a. Examine the processing requirements to conduct navigation onboard and identify CPU, storage, and power requirements
   b. Study how to leverage the limited downlink opportunities in some mission scenarios
3. Identify hardware that can enable improved autonomy; examples include:
   a. Low-power LiDAR for hazard assessment
   b. Sunlight-tolerant imagers with sunglasses, adaptive polarizers, partial sunshade, etc. to improve the dynamic range in extreme lighting environments
   c. Low-power and accurate IMUs for situational awareness

Ocean Worlds Design Reference Mission Report Summary

One of the most profound discoveries resulting from planetary exploration is the evidence for large quantities of liquid water on several bodies in our solar system, aptly named "Ocean Worlds." In an effort to extrapolate our understanding of life on Earth to the cosmos, "go to the water" has become the guiding principle in our search for evidence of extraterrestrial life. Thus, Ocean Worlds have become key astrobiology targets, and many outstanding questions can only be answered through direct contact with their subsurface liquid water. National Research Council (NRC) reports[29,30] and NASA Advisory Groups[31,32] have placed a high priority on the science exploration of our solar system's Ocean Worlds such as Europa and Enceladus. Three major themes are a focus[33]:

- **Geodynamics:** What is the structure and dynamic state of the icy crust and ocean interface?

[29] Space Studies Board, National Research Council. V*ision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press. 2012.
[30] Committee on the Astrobiology Science Strategy for the Search for Life in the Universe, Space Studies Board, National Research Council. *Astrobiology Science Strategy for the Search for Life in the Universe*. doi:10.17226/25252. The National Academies Press. [http://nap.edu/25252] 2018.
[31] Hendrix, Amanda R., T. A. Hurford, and ROW Team. *Roadmaps to Ocean Worlds*. Planetary Science Vision 2050 Workshop #8171. 2017.
[32] Outer Planets Assessment Group Steering Committee. *OPAG Priority Science Questions: Letter to Dr. Lori Glaze, NASA PSD Director*. [https://www.lpi.usra.edu/opag/meetings/aug2019/OPAG-ScienceLetter-to-Glaze_27Aug19.pdf] August 27, 2017.
[33] Hand, K. P., et al. *Report of the Europa Lander Science Definition Team*. [https://europa.nasa.gov/system/downloadable_items/50_Europa_Lander_SDT_Report_2016.pdf] Posted February 2017.

- **Habitability:** Does the Ocean World's past or present state provide the necessary environments to support life?
- **Life Detection:** Did life emerge on one of these Ocean Worlds, and does it persist today?

The challenges involved in implementing robotic subsurface missions on Ocean Worlds are immense, and advanced autonomy may be among the most demanding technology developments that will be required. Ocean Worlds present an environment that is uncertain, dynamic, and communication-constrained, which requires autonomy that is *adaptive*, *reactive*, and *resilient*. For example, the dynamic nature of plume ejecta on Enceladus or the harsh radiation of Europa prohibit human-in-the-loop control, especially during long-duration communication blackouts such as the two-week period during solar conjunction. Ocean World probes must be equipped to *learn* from their interactions with the environment, *react* to imminent hazards, and *make real-time decisions* to respond to anomalies.

The Ocean Worlds DRM team suggests two autonomous DRM scenarios.

DRM Scenario: A Cryobot Concept

This mission consists of a lander that will visit a scientifically interesting spot on the Ocean World’s icy surface and deploy a cryobot to search for life without humans in the loop. The cryobot will be capable of rapid penetration and scientific sampling of thick ice shells down to the ice-ocean interface, where it will deliver an autonomous undersea explorer.
Past and current efforts aimed at identifying mission architectures, key concepts of operations, and technology trades for accelerating the landing and deployment of a cryobot have highlighted the need for a high level of autonomy throughout many of this mission’s phases.

DRM Scenario: A Crevasse Explorer

This mission consists of a lander that will land near a vent plume and deploy an explorer to traverse to a vent opening, anchor and brace itself, and then enter the crevasse to explore. Exploring crevasses and the nearby surfaces on Ocean Worlds presents many challenges including resisting plume forces, dealing with phase changes of water, water vapor occluded imaging, constrained dynamic environments, liquid mobility, and more. Mission operations and scientific discovery will require autonomous capabilities to function in this environment

These DRM scenarios both require a level of autonomy that is not currently available. Advancements in autonomy technology are required for these mission scenarios to perform the following:

Knowledge and Model Building: The surface, vent, and subsurface environments of Ocean Worlds will present significant operational uncertainty, which must be resolved and modeled autonomously. Local-scale models are needed to inform reactive controllers and ensure operational safety, while "global" models are needed to anticipate and plan for critical transition points (e.g., entering the plume stream or the ice-ocean interface).

Hazard Assessment: Mission assets must be capable of characterizing performance hazards that could negatively impact operations and critical hazards that pose mission-ending risks. For example, the Cryobot must be capable of characterizing penetration performance (e.g., speed) over a wide range of ice conditions and defining ice "impurities" that must be avoided, while the Crevasse Explorer must be able to characterize surface hazards (e.g., steep slopes) that will impede traverse and entry into the crevasse and the conditions under which the upward dynamic pressure on the robot will prevent descent. In addition to developing such models, mission assets must be able to conduct an a priori assessment of potential hazards in the environment, detect potential hazards with sufficient resolution to avoid or mitigate them, and then autonomously take preventative action.

Execution and Control: The Cryobot and Crevasse Explorer constitute novel mobility systems that must reliably operate for long periods of time without human intervention. Thus, the capability for autonomous actuation and control to interact with the environment as well as the ability to regulate internal health remain key technology gaps for both systems.

Verification and Validation: System level verification and validation (V&V) approaches for Cryobot and Crevasse Explorer autonomy will require significant development on three primary fronts: (1) uncertainty quantification: rigorous and quantitative studies will be required to define the uncertainty bounds and performance requirements for autonomous operations in the Ocean World environments, (2) physical test beds, and (3) software (simulation) test beds.

Autonomous Science: Due to the multi-hour communication latency to Europa and Enceladus and the dynamic nature of the environments (e.g., the inability to stop for the Cryobot and the time-varying nature of plume ejecta for the Crevasse Explorer), autonomy will be required to perform opportunistic science measurements (e.g., in response to anomalous events or local features that are deemed "interesting") in addition to regularly scheduled measurements. Also, extremely limited data rates will demand that mission assets perform a large degree of autonomous data interpretation, compression, and downlink prioritization.

To enable autonomy in these DRM scenarios, advancements in the following supporting technology areas are required:

- Communications: Deployable RF/acoustic communication puck transceivers to relay data at distance in warm and cryogenic ice; electromechanical tether to support power, communications, and structural support at cryogenic temperatures (70K)
- Mobility Systems: A melt/drill probe that can penetrate an ice sheet and be steerable with a turning radius small enough to avoid obstacles detected with acoustic/RF sensors; a tethered, instrumented, pressurized vessel able to maneuver at the ice-ocean

interface; surface mobility systems to traverse to the rim of a crevasse and descend through the crevasse, reacting against plume forces
- Forward-looking acoustic/RF sensors able to detect hazards and ice/ocean interface: Depth sensing through surface ranging using communication pucks and a sensor architecture for situational awareness in an ocean; visual navigation for surface traversal; flow gradient sensors to follow vent streamlines
- High-performance space computing for inversion of acoustic signals and for real-time visual-inertial navigation across the surface and through vents

Findings

The systems needed to accomplish the goals of these DRM scenarios require a long runway to succeed. Key drivers include time and the critical mass of work required to develop the technology to a point of maturity that reduces the risk for mission implementation. Due to the unique and constraining specifications, the technology development must be requirements-driven and managed, rather than a best effort, technology-push approach. The Ocean Worlds DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above.

1. Develop requirements with traceability to science requirements to be met in the Ocean Worlds environment and that include clearly defined metrics to be used to mature the autonomy systems.
    a. The Ocean Worlds environment should be defined with the fidelity necessary to define environmental requirements on the autonomy technology at the system capability level and at the component level to allow for measurement of technology maturity directly in the context of the DRM.
    b. A product breakdown structure of the complete autonomy system is needed to organize and support maturation of the technology. This structure is a comprehensive, hierarchical structure of deliverables—physical and functional—that make up the autonomy system.
2. Specify a framework for a software simulation and hardware V&V environment that the national community will ultimately build and use to assess autonomy systems. After the framework is specified:
    a. Build an Ocean Worlds software system simulation environment that can simulate the performance of autonomy subsystems and components. Build high-fidelity models of the subsystems and components that will be simulated in the larger system simulation environment.
    b. Build hardware testbeds to experimentally test autonomy subsystems and components.
    c. Construct a community V&V certification framework that will assess proposed autonomy systems against the quantified metrics developed above.

3. Build required system and component software and hardware technologies. The developments will utilize the required DRM environments, product breakdown structures, and V&V environments.

Small Bodies Design Reference Mission Report Summary

Small Bodies, such as near-Earth objects (NEOs), comets, and asteroids, are abundant and have diverse compositions and origins. Exploring them is important to increase our knowledge in four focus areas: decadal science, human exploration, in situ resource utilization, and planetary defense.

Small Bodies are well-suited targets for advancing autonomy because they embody many of the challenges that are representative of even more extreme destinations, but they are accessible by small affordable spacecraft. Autonomy will both enable missions to reach far more diverse bodies and enable greater access to those bodies than the current ground-in-the-loop exploration paradigm. Operating near, on, or inside these bodies is challenging because of their largely unknown, highly-rugged topographies and because of the dynamic nature of the interaction between the spacecraft and the body. Many previous Small Body missions have used some level of autonomy, but all operated within narrow windows and constraints. The missions proposed by the Small Bodies DRM team require autonomy to overcome these challenges and achieve effective mission operations.

The Small Bodies DRM team suggests two autonomous DRM scenarios.

DRM Scenario: A Mission from Earth's Orbit to the Surface of a Small Body

This scenario is a near-term mission (launch in 2030s) that places an affordable small satellite in Earth orbit with a high-level goal of reaching a selected asteroid, approaching and landing on the body, precisely accessing at least one target on the surface, sampling, analyzing the measurements, retargeting follow-on measurements based on local analyses, and sending the results back to Earth—all of which are accomplished autonomously.

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:

End-to-end, Long-Duration Autonomy: Operating for a long duration in spite of unknowns, degradations, faults, and failures is crucial. So far, autonomous capabilities have only been used for relatively short mission durations with pre- and often post-monitoring from the ground. This mission must be capable of establishing situational- and self-awareness and reasoning and acting under a wide range of conditions that include detecting faults and failures and mitigating the problem(s).

Approaching and Landing on a Body: During approach, autonomy is needed to observe, track, and model the body's trajectory, rotation, and shape at distances from thousands of kilometers (when uncertainties are large) down to the surface to avoid collision. During this operation, autonomy is also required to refine knowledge of the spacecraft's motion and command its maneuvers. Autonomy will allow use of onboard models to assess the hazards in the environment at the scale of the spacecraft to identify, avoid, guide and land the spacecraft at a safe location, while minimizing its consumption of resources. Today, such feats take months of human-intensive operations.

Handling the Environment: Autonomy is needed to handle large uncertainties that result from the irregular topography, low gravity, debris near the surface, and dynamic conditions that arise from outgassing or ejection of blocks or particles. The spacecraft must be able to autonomously monitor and react to such conditions in real time with limited a priori knowledge of the environment.

Proximity Interaction: Autonomy is necessary to handle physical interactions with an unknown environment. Exploration near, onto, or into the surface requires an understanding of the body's geophysical properties and the dynamic interaction between the spacecraft and the low-gravity body. Models have to be generated and actions taken in real time. The mission needs to adapt and learn from its operations autonomously.

Reaching Specific Surface Targets: Autonomy is required to establish situational-awareness while on the surface, assess hazards for mobility, and plan and execute motions to reach multiple and specific destinations on the surface within specific timeframes and resources. Autonomy is needed to continually localize the spacecraft on the surface and update its knowledge of the environment. Surface mobility would be highly stochastic due to large variations in topography and local gravity.

Manipulating the Surface or Subsurface: Autonomy is required for analyzing and identifying samples for collection and sample handling.

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

- Small satellite propulsion with delta V > 1,000 m/s
- Advanced onboard computing and storage
- Advanced sensing and optics
- Surface mobility and mechanisms for subsurface access
- Low mass, low-power, direct-to-Earth communication from small spacecraft

DRM Scenario: Mother/Daughter Craft to Understand the Small-Body Population

This long-term DRM scenario (launch in 2040+) scenario places a centralized mother platform with multiple daughter satellites in Earth orbit to scan, identify, characterize, and eventually enable access to a range of Small Bodies. The mother craft will dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar or hazardous objects). These daughter craft will visit the targets to collect samples and return material to the mother craft for further analysis or for resource extraction.

This DRM scenario requires a level of autonomy that is not currently available. In addition to the autonomy technology advancements required by the mission scenario described above (Mission from Earth's Orbit to the Surface of a Small Body), further advancements in autonomy technology are required for this Mother/Daughter Craft mission scenario to perform the following:

Extracting Resources: Autonomy is required to enable anchoring or holding on to the surface and reaching deep into the body—activities which depend on instantaneous local conditions. Autonomy is also needed to support extraction and handling of large volumes of material for processing.

Detecting Small Bodies and Coordinating Multiple Spacecraft: Autonomy is needed to identify Small Bodies in space based on intent, then track and estimate their trajectories. Autonomy is also needed to plan cruise trajectories to the body, coordinate between the mother and daughter spacecraft, and dispatch appropriate daughter spacecraft to specific bodies. For long-term operations, autonomy is required to enable daughter spacecraft to return to the mother, dock and refuel.

Planetary Defense: Planetary defense requires (1) understanding the composition and geotechnical properties of Small Bodies and (2) threat mitigation that demands dealing with a largely unknown interior and surface. Both the understanding and mitigation are best accomplished with autonomous spacecraft. Furthermore, several deflection scenarios, such as a kinetic impactor or gravity tractoring, require the spacecraft to navigate autonomously due to the need to adjust the trajectory in real time.

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

- Low-mass replenishable propulsion with initial delta V > 5,000 m/s
- Docking/undocking with ability to transfer volatiles
- Advanced onboard computing and storage for long-term operations
- Advanced sensing and optics for remote detection
- Large-scale surface mobility, subsurface excavation, and material handling
- Communication among multiple assets in space, on the surface, and below the surface

Investments in autonomy for Small-Body missions will provide the Agency with far-reaching benefits. Implementing autonomy to enable Small Body missions will provide a "sandbox" for researching, developing, testing, and maturing technologies that can be used in more complex, less forgiving, and more expensive mission scenarios. Small Bodies are accessible, diverse, and plentiful. Small Body research embodies challenges that are common to several other DRMs:

- Unknown topography for mapping and characterizing
- A priori unknown surface properties
- Extremely rugged surfaces (Europa, Enceladus)
- Interaction between assets and the environment (Venus, Titan, liquid bodies, etc.)
- Dynamically hazardous environments (Europa, Enceladus's plumes)
- Obstructions to line-of-sight communications (Titan, Enceladus's vents, Europa's crevasses)

In addition, Small Body missions have certain advantages that would enable technology development:

- Lower cost for approach and landing
- More forgiving (impact with surface is less harmful, slower motions)
- Accessible via small spacecraft
- Offer missions of opportunity (flybys of interstellar visitors)

Findings

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

1. Establish a one-year project with participation from NASA/industry/academia to flesh out the design details; assess the applicability of external technologies (automotive and logistics industries/government agencies) and identify detailed gaps; provide specification for supporting technologies, including rapid systems engineering; and estimate the cost of developing and verifying/validating the various capabilities
2. Define crisp engineering challenges to seed solicitations for:
    a. Developing a high-fidelity, end-to-end, physics-based simulation to support the development of a fully-autonomous mission to a Small Body using small spacecraft
    b. Developing and maturing the key autonomy technologies using the full lifecycle simulation
3. Establish a project to integrate hardware and software capabilities, test them in simulation, and mature them for flight demonstration
4. Demonstrate capabilities of increased sophistication via a couple of small spacecraft missions and/or extended missions of opportunity

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