

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: DRM Team Summary Reports

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Introduction

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

The Workshop goals included:

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

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

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

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

This document contains a summary of the post-workshop findings followed by the eight DRM team summary reports. [The DRM team full reports can be accessed online](#).

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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 <u>or</u> 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.

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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.

DRM TEAM SUMMARY REPORTS

Astrophysics Design Reference Mission Report Summary

In the Exoplanet Science Strategy Report¹, 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 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

¹ National Academies of Sciences, Engineering, and Medicine. *Exoplanet Science Strategy*. Washington, DC: The National Academies Press. [<https://doi.org/10.17226/25187>] 2018.

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- 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

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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

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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

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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

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- 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.

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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,”² 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

² McNutt, et al. *Interstellar Probe: Humanity's Journey to Interstellar Space*. [<http://interstellarprobe.jhuapl.edu>] 2019.

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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 4π 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 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.

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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,

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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

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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.

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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

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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.

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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 Survey³ and Lunar Exploration Roadmap⁴ 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

³ 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>].

⁴ 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>].

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[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 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.

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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

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Council (NRC) reports^{5,6} and NASA Advisory Groups^{7,8} 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 focus⁹:

- **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?

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.

⁵ Space Studies Board, National Research Council. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press. 2012.

⁶ 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.

⁷ Hendrix, Amanda R., T. A. Hurford, and ROW Team. *Roadmaps to Ocean Worlds*. Planetary Science Vision 2050 Workshop #8171. 2017.

⁸ 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.

⁹ 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.

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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

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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.

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- 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

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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-

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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.

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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 tractor, 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

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- 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

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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

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- 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-

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.

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