National Aeronautics and
Space Administration

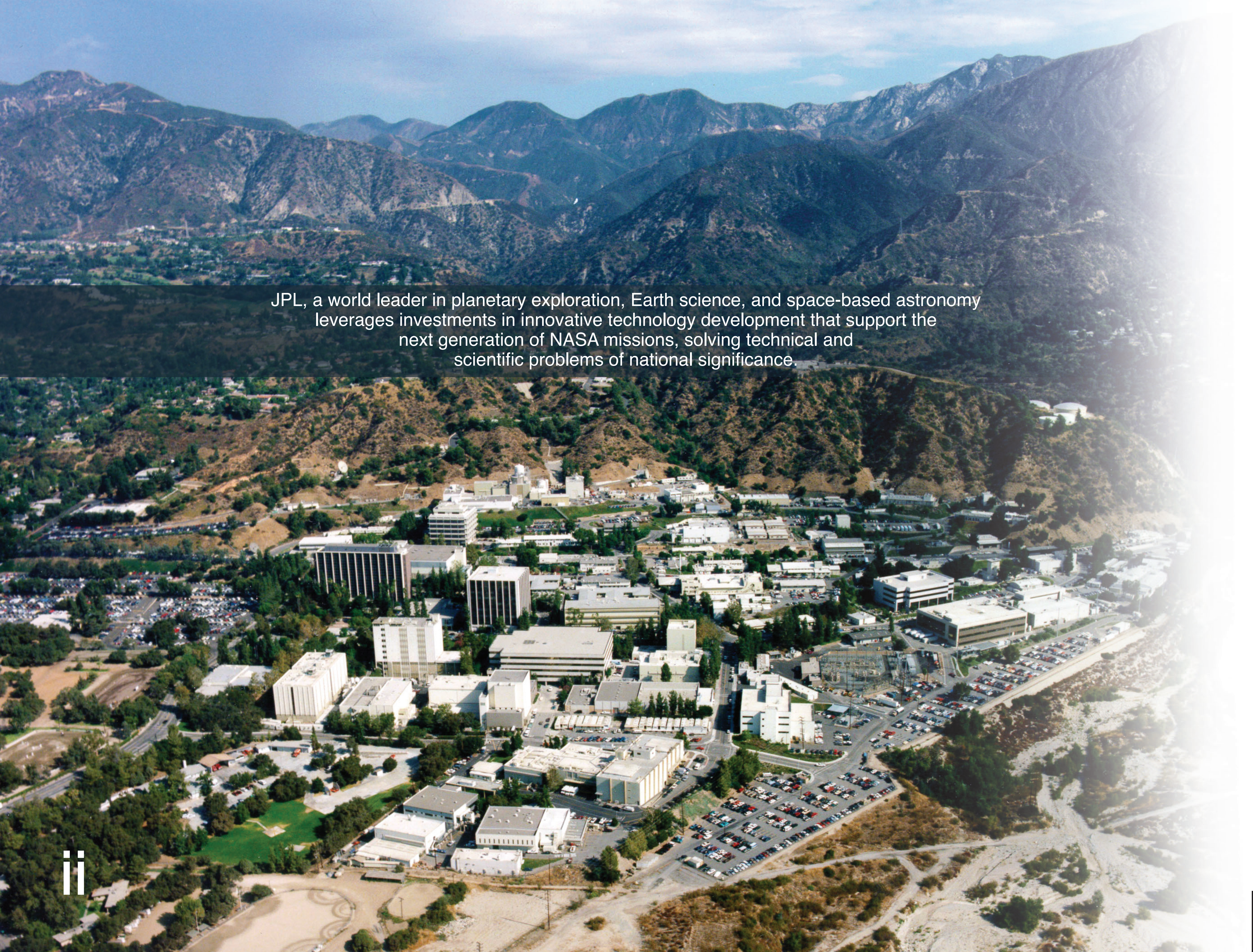
JET PROPULSION LABORATORY

STRATEGIC TECHNOLOGIES

2019

This document expresses a strategic intent on behalf of the Jet Propulsion Laboratory to emphasize nine technology thrusts through preferential investment and recruitment.

CONTENTS



JPL, a world leader in planetary exploration, Earth science, and space-based astronomy leverages investments in innovative technology development that support the next generation of NASA missions, solving technical and scientific problems of national significance.

DIRECTOR'S MESSAGE

In pursuit of our Quests, JPL envisions exciting new missions that extend our reach, deepen our understanding, and enhance every opportunity for scientific discovery.

New missions for astrophysics, astronomy, and cosmology will reveal details of distant systems at a level of granularity never before possible. With coordinated systems forming the largest apertures in history, we will receive faint signals at the submillimeter level, peering into the depths of the universe, and we will gather and piece together multi-pixel images of exoplanets orbiting distant stars, revealing patterns of oceans and clouds. With more powerful and more intelligent processing systems, we will quickly prioritize and analyze more data than ever, leading to faster and more comprehensive discoveries on the formation and evolution of individual planets and entire galaxies.

Ambitious planetary science missions will explore new surface features, atmospheres, and even subsurface oceans. New mobility systems with greater autonomy will explore features of Mars beyond the reach of our current rovers, rappelling down cliffs to study layered deposits or investigating miles of lava tubes to search for signatures of life. Robust systems will survive the extreme pressure and high temperatures on Venus to study the evolution of its toxic atmosphere in the first-ever long-duration missions to the destination. Missions to ocean worlds, such as Europa, Enceladus, and Titan, will use sophisticated robotic systems to navigate and sample the first bodies of water encountered off Earth. With stronger communication systems, our ground operations will more quickly receive larger amounts of data collected in situ from these diverse environments, informing our understanding of the potential for life in their past or present or for human exploration in their future.

Closer to home, Earth science missions will employ greater coverage of smarter technologies that can manage the complexity of Earth's interconnected and intertwined systems. We will better understand the role of natural, industrial, and historical factors in changes to Earth's weather, oceans, and atmosphere, so that we might better predict short-term events, such as hurricanes, and mitigate long-term events, such as coastal flooding and globally rising temperatures.

These missions become possible with JPL's long-term investment in the technology areas that *Strategic Technologies* describes. As the report explains, we face many challenges to realizing these bold visions, but overcoming such challenges is what has made and will continue to make JPL a leader in technological and scientific innovation.

— Dr. Michael Watkins

Extraordinary scientific achievements require considerable forward-thinking investment in research and technology development. This document is dedicated to the JPL innovators whose skill, vision, creativity, leadership, and resolve make these achievements possible.

CHIEF TECHNOLOGIST'S MESSAGE

JPL's Quests drive our technology development. We have ambitious goals to expand our understanding of the complex systems that shape our world, from the cycles that drive Earth's climate to the forces that reveal the origins of the Universe. Achieving these goals demands huge strides in technology development—for stronger and smarter systems with savings in mass, power, time, and cost. Every technology area we advance further will either support or be supported by advancements in another area.

Our top priority is autonomy. Fully autonomous systems will function without human intervention: moving, seeing, thinking, learning, and acting on their own. Artificial intelligence and machine learning (AI/ML) will give the autonomous system its decision making capabilities, drawing on massive libraries and efficient analysis made possible by innovations in data science. The autonomous system will be fully aware of its environment with the use of increasingly sophisticated instruments and sensors, which will also enable the system to observe distant phenomena and collect samples in situ. These developments will empower JPL with the tools it needs to pursue the Quests while also reducing risk and cost.

All JPL missions have been and will continue to be robotic. Robotics and mobility systems will become more capable, more durable, and more autonomous, benefitting from every technology development that improves autonomous systems. Advanced manufacturing, design, and materials will strengthen and enhance robotics systems while decreasing the craft's mass, power needs, and time to development.

New approaches to communication and navigation will help robotics systems maintain their connection to Earth while following complex trajectories to reach more scientific targets of interest, many of which have never been explored by any mission from Earth.

Drawing on developments in autonomy and robotics, JPL will achieve an all new capability with distributed systems of spacecraft. With advancements in miniaturized systems, a distributed system of hundreds or thousands of small satellites will configure as apertures larger than anything that can be launched as a monolithic spacecraft, so JPL can gather weak signals coming from the farthest reaches of the universe. With new developments in communication and navigation, the individual assets of the distributed system will remain perfectly synchronized. The redundancy and harmony of the system will maximize science return while minimizing risk.

Collectively, the technologies we describe in *Strategic Technologies* not only enable us to answer our guiding Quests but also challenge JPL to change our approach to system design, engineering, and operation to remain at the forefront of scientific discovery.

— Dr. Fred Hadaegh

INTRODUCTION

This report highlights nine priority areas for JPL to lead technology development over the next 20 years.

The goal of this document is to present strategic technologies that will enable 2030-2035 science missions in pursuit of the JPL Quests:

01 Understand how Earth works as a system and how it is changing

02 Help pave the way for human exploration of space

03 Understand how our Solar System formed and how it is evolving

04 Understand how life emerged on Earth and possibly elsewhere in our Solar System

05 Understand the diversity of planetary systems in our galaxy

06 Understand how the Universe began and how it is evolving

07 Use our unique expertise to benefit the nation and planet Earth

Therefore, this report describes systems, tools, and techniques that require significant time for maturation but ultimately enable the complex and ambitious missions that the Quests demand.

Nine chapters focus on each of the priority technologies:

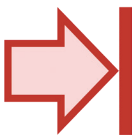
- Autonomous Systems
- Artificial Intelligence and Machine Learning
- Data Science
- Miniaturized Systems
- Advanced Manufacturing, Design, and Materials
- Distributed Systems
- Communication and Navigation
- Instruments and Sensors
- Robotics and Mobility Systems

The first six chapters describe disruptive technology areas, which result in system-level changes in future space system design and implementation. The last three describe core competencies in which JPL currently leads technology development and must continue to lead to enable its future missions.

Each chapter defines the priority area and summarizes its envisioned benefits, current challenges, and potential solutions in four sections:

ROLE IN SCIENTIFIC DISCOVERY: details scenarios in which new technology enhances astronomy, astrophysics, cosmology, Earth science, and planetary science within the 2030–2035 timeframe.

BENEFIT TO JPL MISSIONS: describes how the new technology enables and improves future JPL missions, in terms of reductions in cost and risk, reduced time to development, increased flexibility and scalability, and enhanced science return.



CHALLENGES: explains the challenges that the new technology must overcome to make these future missions possible, in terms of limitations of the current state of the art and obstacles specific to different missions.

SOLUTIONS: identifies specific areas for long-term investment and potential technology directions within each area.

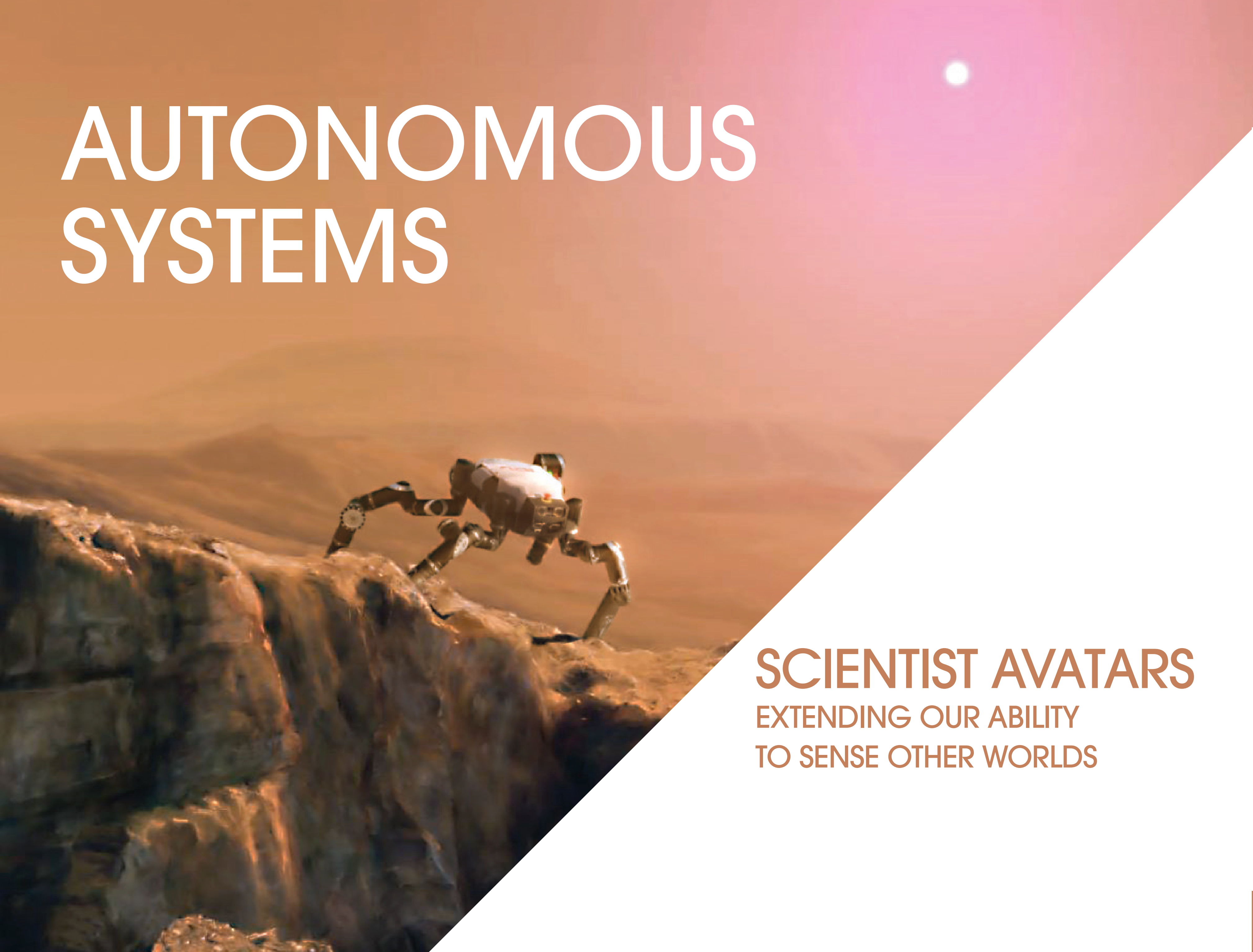
As a distinct unit, each chapter describes how and why JPL plans to pursue advancements in that priority area, while also highlighting how advancements in one area enable or require advancements in others. Therefore, readers can use individual chapters as well as the cohesive report to understand how JPL prioritizes technology development in the next two to three decades to achieve its envisioned missions and answer its Quests.

METHODOLOGY

The development of this document involved the broad participation of JPL's science and technology communities and programmatic leadership. This document was developed in significant coordination with the 2018 JPL Strategic Implementation Plan (SIP). The full strategic traceability is presented in Appendix B. The technologies described herein correspond to the SIP Future Capabilities, as seen in Appendix C.

The Office of the Chief Technologist (OCT) conducted reviews of National Academy of Sciences Decadal Surveys, as well as a series of studies conducted by NASA OCT over the course of several years to identify NASA technology priorities. The OCT solicited participation from a broad set of stakeholders. Discussions were held with JPL Program Directorates to determine how their plans for the 2030-2035 timeframe depend on advanced technology. Directorate and Division Chief Technologists and Chief Scientists, as well as other subject matter experts, contributed to the content and review of this document. This document was presented to and reviewed by the JPL Strategic Planning Management Council.

AUTONOMOUS SYSTEMS



SCIENTIST AVATARS

EXTENDING OUR ABILITY TO SENSE OTHER WORLDS

INTRODUCTION

Autonomous systems enable spacecraft or other robotic platforms to make decisions and take actions without human intervention. This is often described as a perceive-decide-act loop. Using onboard models and information from sensors, autonomous systems can accomplish mission goals with limited commanding from Earth, even in the face of uncertainty.

The degree to which spacecraft can adjust to the uncertain or unexpected without human intervention has historically been quite limited. Enabling spacecraft to rapidly assess and react to events and environments, increases the reliability and productivity of missions. Some future missions will have limited communication with Earth for extended periods of time, such as drilling through kilometers of icy crust on Europa, requiring the systems to be able to assess their own environment and make decisions independently. Other missions will require reacting on a timeframe that is shorter than the communication time with Earth such as sampling from short-lived plumes. Missions that cannot receive commands from Earth quickly and reliably will need the autonomous capability to explore with reduced or no human intervention.

Autonomy can increase spacecraft productivity and, when the spacecraft cannot wait for ground commands, enable rapid reactions. As JPL continues to develop and fly increasingly complex missions, spacecraft autonomy will be a key element in the success and increased science return of these missions.

ROLE IN SCIENTIFIC DISCOVERY

With advanced autonomy, spacecraft and robotic measurement systems can reach and explore environments that are otherwise unattainable. Rather than rely on programmed commands, a spacecraft is aware of its surroundings at all times and capable of determining and executing safe and effective actions. Vehicles can navigate in uncharted territory, such as the oceans of Enceladus, deep caves on Mars, or drilling through deep layers of ice. Spacecraft can rapidly respond to phenomena with short encounter periods, such as witnessing a plume on Europa. By no longer relying on delayed and limited commands from Earth, science missions are more productive and robust, and new opportunities for discovery become available for the first time.

BENEFIT TO JPL MISSIONS

Autonomous systems improve reliability and productivity while reducing risk and operational costs, and potentially lowering development costs. Some missions can only happen with autonomous systems.

Missions that face critical time constraints benefit from autonomous systems. When the actions of these spacecraft are resource-limited, or when the environment is highly unpredictable, decisions

Opposite: A RoboSimian-like autonomous robot assesses its next move near a cliff on Mars.

to act cannot wait for communication with Earth. For example, a lander sent to Venus might have only a few hours to complete its science goals before succumbing to the harsh environment. Alternatively, a lead spacecraft in a multi-agent mission around Earth or another planet might detect and recognize an emerging storm in time for a secondary spacecraft to retarget itself and gather key information. The time saved by equipping the spacecraft with an autonomous system can enable new scientific discovery and optimize a resource or time-constrained mission.

CHALLENGES

The need for autonomy in space exploration is driven by uncertainty and unexpected changes in the spacecraft state and environment, oupled with communications constraints, such nmunication windows, light time communication and limited bandwidth. Ambitious future exploration l lead to complex mission scenarios and spacecraft systems. Limited reaction time and mission lifetime can both precipitate advances in autonomy. Destinations where exploration is time critical include Venus balloons, Titan aerobots, and in-situ missions to ocean worlds such as Europa and Enceladus. Tightly coupled fleets of spacecraft for monitoring changes on Earth, space weather, exoplanet detection, and other distributed systems will require streamlined operations and increased autonomy for individual spacecraft. The capability to quickly understand onboard and to act using different types of data is necessary for autonomous missions to operate in unfamiliar, remote environments.

SOLUTIONS

JPL addresses these challenges by advancing autonomous systems technology in three areas: sensing for situational and self-awareness; onboard reasoning for determining actions to achieve goals and manage health; and systems

Fully autonomous robots can traverse unfamiliar, hard-to-reach locations.

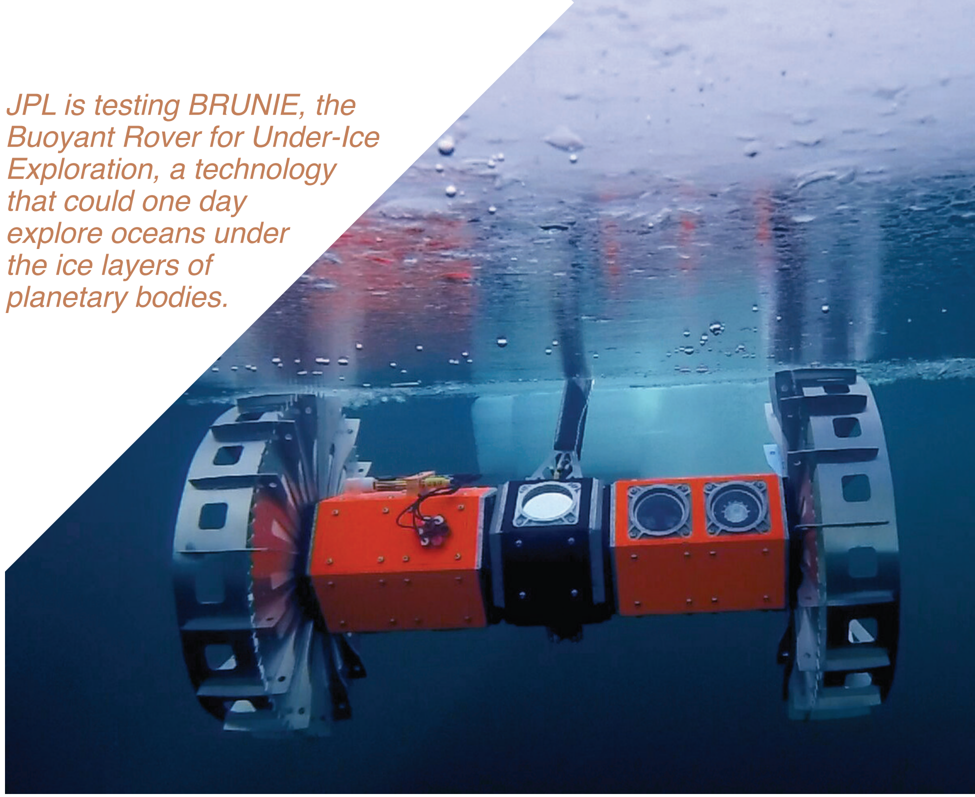
engineering considerations for architectures, operations, and verification and validation. These areas also relate to the technology solutions described in Artificial Intelligence and Machine Learning, Data Science, Instruments and Sensors, and Robotics and Mobility Systems.

Situational Awareness and Self-Awareness

To operate autonomously, a system must be aware of its surrounding environment and its own operating state. Situational awareness includes the ability to self-localize, detect hazards, and monitor significant changes in phenomena that might indicate key scientific data. Meanwhile, self-awareness ensures system resilience and robustness by monitoring, diagnosing, predicting, and assessing system health. Together, situational awareness and self-awareness capabilities enable areas such as self-navigation.

With onboard science operations, an analysis of science data in conjunction with onboard science models enables a spacecraft to identify features deemed scientifically interesting, particularly those with short encounter periods. The onboard identification of such features enables the spacecraft to prioritize data for rapid downlink or to autonomously collect additional data and train additional instruments on features of interest. To enable these operations, JPL must develop techniques for event detection and feature identification using different data types obtained from multiple sources. JPL also needs technology that can adapt to harsh or dim lighting.

With autonomous navigation, a spacecraft performs its own navigation functions without contact with Earth. Advancements in autonomous navigation must address a broader range of mission applications, including cruising anywhere in the Solar System, planetary approach, orbit insertion and maintenance, planetary landings and flybys, outer planet satellite tours, small body proximity operations and landings, and rendezvous and sample capture in Mars orbit.



JPL is testing BRUNIE, the Buoyant Rover for Under-Ice Exploration, a technology that could one day explore oceans under the ice layers of planetary bodies.

Onboard Reasoning and Decision Making

Onboard reasoning and decision making are essential to protecting a spacecraft and for planning actions.

A spacecraft's health monitoring and management system relies on onboard reasoning and decision making. Also called a fault detection, isolation, and recovery system, this system helps a spacecraft protect its ability to achieve mission objectives. With increasingly complex spacecraft, adaptive health management systems must be fully integrated with onboard control systems. As a spacecraft and its environment change, an adaptive health management system adjusts the system configuration to eliminate the distinction between

Self-navigation is crucial for missions subject to communication lag, such as an underwater mission on Europa.

nominal and faulty operations. To achieve an adaptive system, JPL needs advances in on-the-fly goal elaboration, approaches for modeling the system at a meaningful level of fidelity, and artificial intelligence and algorithms for assessing the current state and reasoning with the modeling system.

Onboard reasoning and decision making also enable the planning and scheduling of activities that a spacecraft executes. After autonomously assessing current conditions and the results of prior commands, goal-based planning can adjust and execute activities without relying on commands or prior assessments from Earth. One important activity to plan and schedule autonomously is path planning for landed missions. Autonomous path planning requires advances in terrain classification algorithms that can identify hazards from image analysis and determine paths to avoid the hazards. Another important activity is the autonomous optimization of observation schedules, which requires equipping spacecraft with both geometric-aware and resource-aware reasoning.

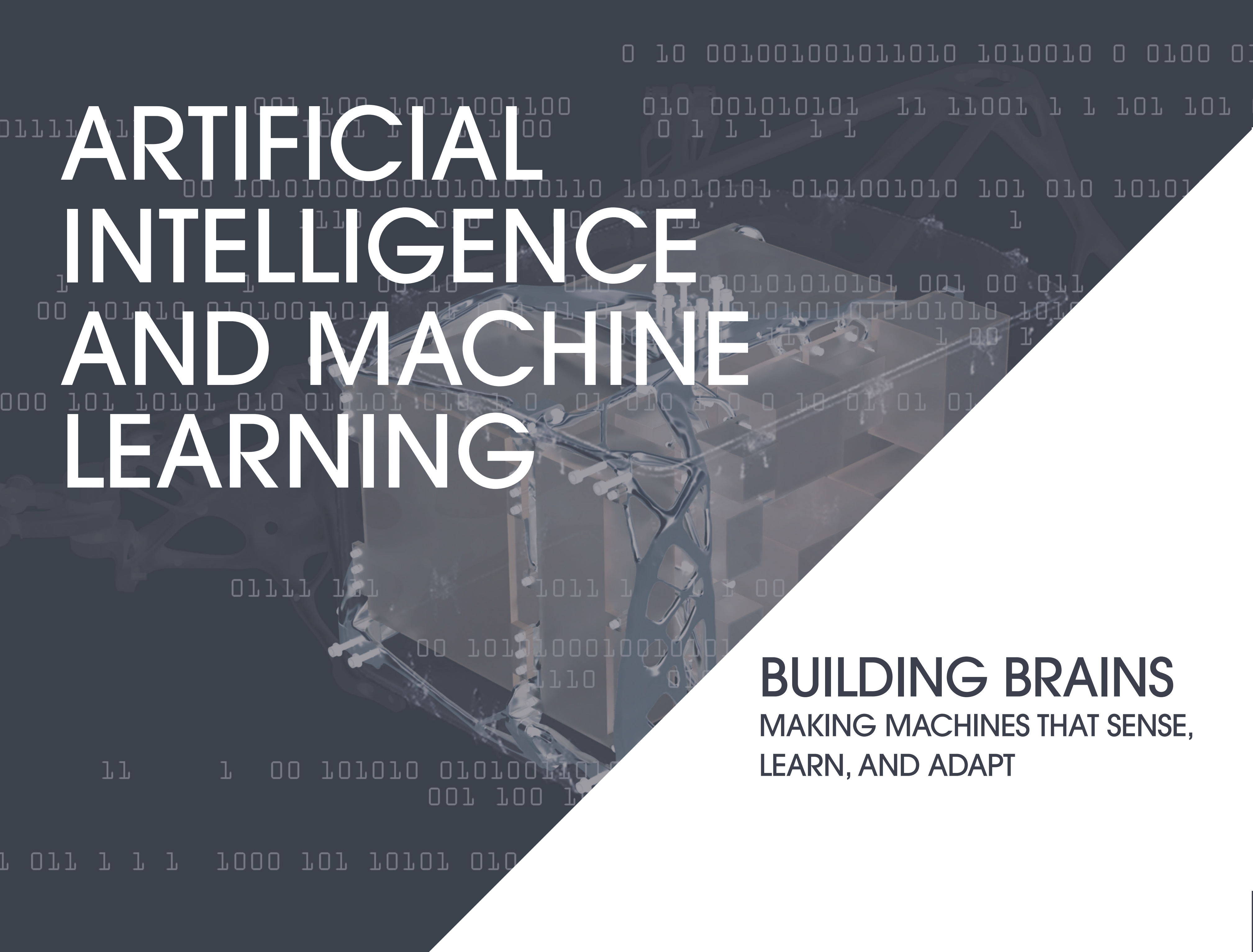
Architectures for Autonomous Space Systems

As autonomy becomes more central to operations, spacecraft designers must incorporate autonomous systems into the architecture of the entire mission, to realize the full benefits of an autonomous system. When individual autonomous capabilities can interact with each other, the whole system is more capable than the separate elements. To incorporate autonomy into the entire system design, JPL must increase research and development efforts in areas such as goal-based commanding and verification and validation (V&V).

Goal-based commanding enables the ground to specify intent and the spacecraft to robustly achieve the specified goals. JPL needs innovative approaches to intuitively capture operator intent, operational trust building, and user design and interaction. JPL also needs techniques to determine the minimal necessary data for operator decision making and troubleshooting under high levels of execution uncertainty.

Autonomous systems must undergo rigorous V&V. JPL must develop a systematic and scalable V&V approach with a mix of formal methods, simulation, modeling, analysis, hardware-in-the-loop testing, analogous testbeds, field testing, and incremental deployment for using autonomous systems in new or unknown operations. Because a fully integrated autonomous system should have an onboard autonomous recovery capability, the V&V approach must also include a combination of perception and state estimation; reflexive responses; and onboard elaboration, planning, and scheduling to determine and conduct anomaly recovery.

An autonomous telescope selects which targets to analyze in greater detail using onboard software.



ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

BUILDING BRAINS

MAKING MACHINES THAT SENSE, LEARN, AND ADAPT

INTRODUCTION

Artificial Intelligence and Machine Learning (AI/ML) enable tasks that otherwise require human intelligence and human intervention. In addition, AI/ML are key enabling components of autonomy and are core to data science.

A spacecraft autonomously exploring in an unfamiliar environment will use AI/ML to interpret data from multiple sources, then use that interpretation to determine its next steps. On the ground, AI/ML will be used to synthesize and analyze data for both science understanding and mission operations, as science missions gather increasingly larger volumes and more diverse types of data.

AI enables a computing platform to operate beyond straightforward automation. The algorithms behind AI mimic human approaches to planning, understanding language, recognizing objects and sounds, solving problems and learning. ML provides the capability to analyze large data sets to identify patterns and provide insight.

ROLE IN SCIENTIFIC DISCOVERY

AI/ML directly enable scientific discovery through analysis of model and measurement data across, all JPL scientific domains. AI/ML detect patterns and relationships within the growing expanse of scientific data helping to understand the complex interactions within Earth, planetary, solar, and galactic systems. For example, AI/ML techniques applied to Earth observation and Earth model data provide insights into the multifaceted interconnection of the water and carbon cycles and changes in climate, sea levels, weather, Earth's surface, and Earth's interior.

With AI/ML, spacecraft can complete more distant and complex missions by analyzing onboard countless diverse data to autonomously decide the best path forward. Thus, AI/ML support scientific advances by enabling autonomous spacecraft to access, explore, and sample remote locations such as caves and under-ice oceans. AI/ML also increase science by enabling the spacecraft to observe dynamic events as they evolve such as plume eruptions, collecting and analyzing data to answer questions of how the diverse bodies of the solar system formed and are changing, as well as searching for life beyond Earth.

BENEFIT TO JPL MISSIONS

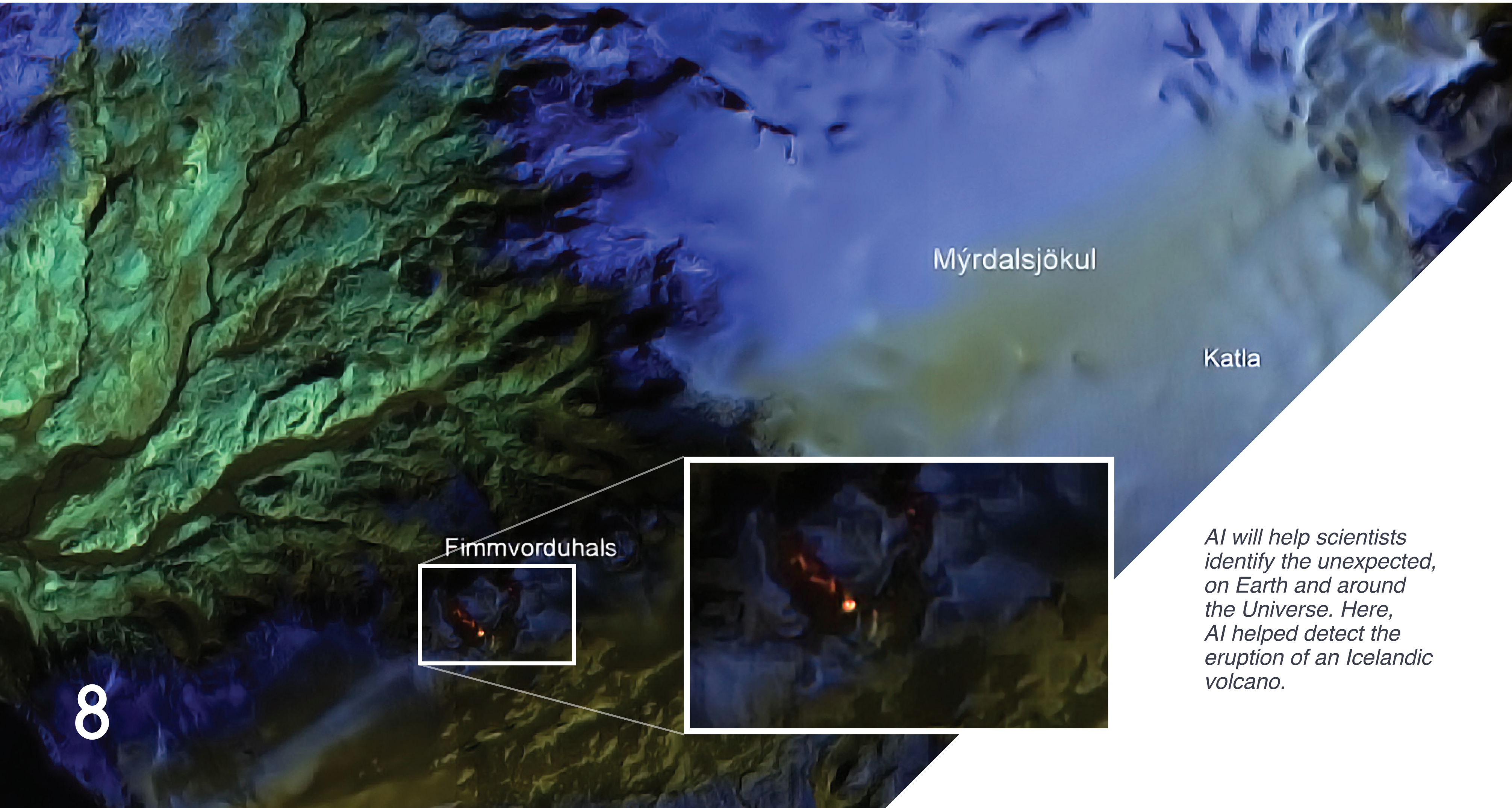
Incorporating AI/ML in spacecraft design and data analysis can significantly reduce the cost of ground operations and enable missions to operate in uncertain environments. With AI/ML,

Opposite: A computer generated graphic of the core systems in a spider-like Europa Lander concept designed by JPL and Autodesk with the assistance of AI under Project Gamma.

deep space missions will mitigate data rate limitations and communication delays by summarizing and prioritizing data for transmission. When autonomous spacecraft encounter new challenges, AI/ML will enable the spacecraft to integrate different types of data from the environment and then learn how to adapt. Solving complex problems, such as real-time optimization of non-convex functions, will increasingly benefit from AI/ML as an analysis tool. AI/ML will also advance the engineering and design of sophisticated systems for use on Earth and in Space.

CHALLENGES

Growing volumes of data returned by space missions and generated by models, coupled with system complexity, are challenging traditional analysis methods for design, engineering, science, and operations. Onboard, the capacity of instruments to generate much more data than can be stored or transmitted to Earth due to bandwidth constraints, leads to a need for real-time analysis to prioritize and



AI will help scientists identify the unexpected, on Earth and around the Universe. Here, AI helped detect the eruption of an Icelandic volcano.

summarize the information before sending. Spacecraft that need to react or adjust to events in less time than it takes for round trip communications to Earth need to autonomously analyze sensor data and make onboard decisions.

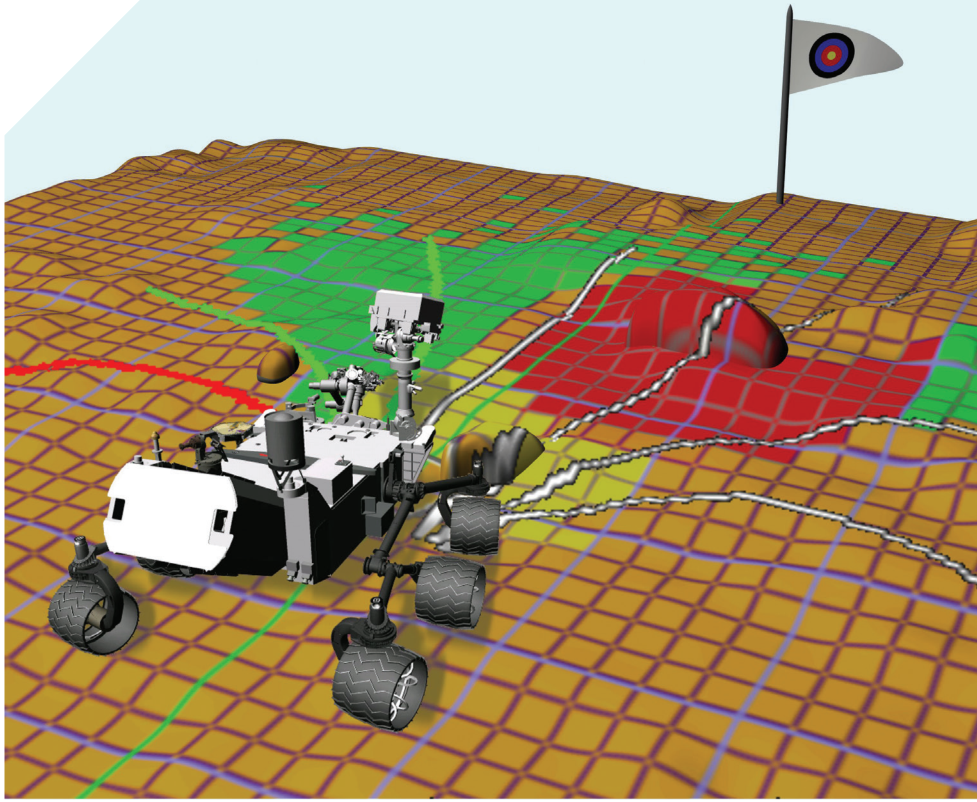
Fully integrated autonomy in spacecraft is also a systems engineering challenge. Historically, only individual autonomy components of a system have been incorporated after the initial system design and development. The lack of integration and planning has prevented systems from becoming fully autonomous, limiting their efficacy. A fully autonomous system requires total integration from the start of the design and development.

JPL science missions collect large volumes and diverse types of data. However, spacecraft cannot store the volumes of data, and due to bandwidth constraints, cannot transmit the data to Earth in time to relieve onboard storage. Furthermore, current data analysis approaches cannot make sense of different data types efficiently, if at all. The capability to quickly understand and act on different types of data is necessary for autonomous missions to operate in unfamiliar, remote environments.

Deep space missions have communication delays. Moreover, a mission may be inaccessible to communications from Earth. Missions that cannot receive commands from Earth quickly and reliably must have the capability to adapt to environments without human intervention. Advances in autonomy and AI/ML are necessary for these missions.

SOLUTIONS

To address these challenges, JPL must incorporate AI/ML in spacecraft and systems on the ground, including data-driven learning approaches and model-based reasoning. These areas also relate to the technology solutions described in Autonomous Systems, Data Science, Instruments and Sensors, and Robotics and Mobility Systems.



Mars Science Laboratory (MSL) autonomous navigation: operators bound the space, the rover interprets the terrain, and a 3D view of the rover in a similar terrain.

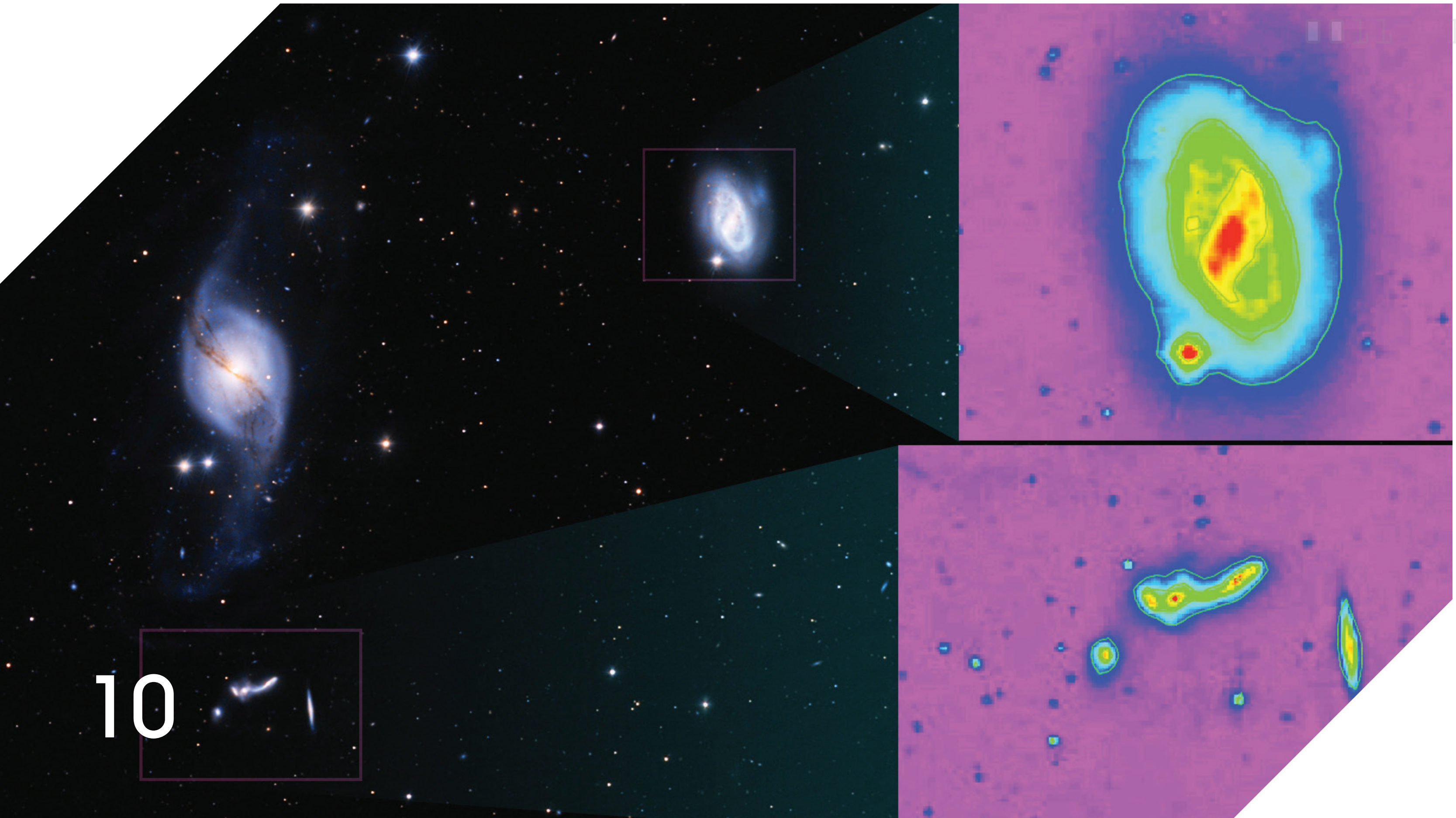
Data-Driven Learning

Data-driven learning identifies patterns in large data sets. Data-driven learning trains a system to classify large amounts of new and diverse data input. A trained system can detect and analyze changes, features, anomalies, and trends. These systems enable terrain estimation, atmospheric correction, and object or event classification. Potential data-driven learning approaches to develop include unsupervised learning and knowledge distillation.

Unsupervised learning, which includes transfer learning, is a form of data-driven learning that can use data without labels.

For example, with transfer learning, a system trained with a large dataset in one domain is incrementally retrained with few examples from the new domain. This ability to retrain with limited data enables a system to adapt quickly to uncertain environments and to pursue unanticipated challenges and goals.

Knowledge distillation is a technique that trains a smaller neural network to perform similarly to an original network. When onboard training is required, such as during landed missions to new destinations or subsurface exploration, knowledge distillation can enable a system to adapt to the environment without prior knowledge.



Machine learning algorithms are "taught" to recognize astrophysical similarities to analyze galaxies.

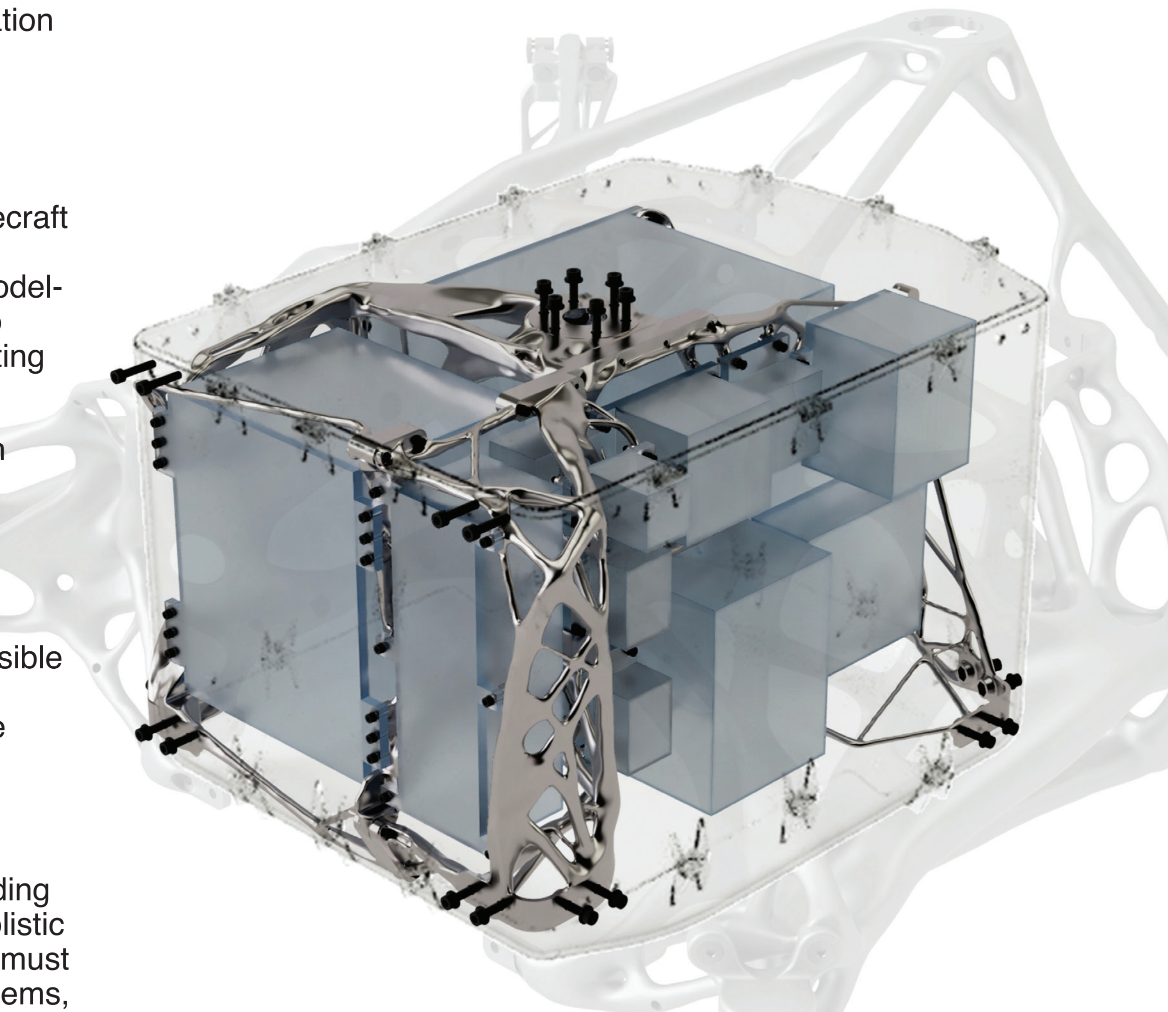
Model-Based Reasoning

With model-based reasoning, a spacecraft can update its plan without manual enumeration and explicit elaboration of every scenario or state in the system design. Approaches to model-based reasoning might include model-driven observation, hypothesis generation and testing, and reasoning across models.

Model-driven observation enables autonomous spacecraft to determine the potential information gain from an observation, using an analysis of physical models. Model-driven observation requires new sensing strategies to select which data to collect, while accounting for existing resources and constraints.

Hypothesis generation and testing can enable system diagnosis or the answering of scientific questions. For example, with hypothesis generation and testing, a spacecraft can autonomously determine whether an observed crater was formed by a meteor impact or a volcano. The spacecraft's system generates a hypothesis by reasoning from a model to a set of possible explanations for the observations. It then tests the hypothesis to see whether it can account for available observations, and finally discriminates between the hypotheses that survive testing, requesting additional observations as necessary.

Reasoning across models yields a holistic understanding of interconnected systems. For example, to form a holistic understanding of Earth's changing climate, scientists must combine physical models of many interacting subsystems, including atmosphere, ocean, and ice shelves. Although the time constant for changes in these subsystems ranges from minutes to hours for atmospheric effects to decades and longer for ice sheets, a reasoning across models approach can efficiently integrate these different models for a holistic view.



This computer model shows the internal structure of an AI-enabled, generatively-designed, spider-like Europa lander. It is just one example of how AI/ML will impact not only mission data return and operations, but systems engineering and design as well.

DATA SCIENCE

SIMPLIFYING COMPLEXITY

TRANSLATING DATA INTO USABLE INFORMATION

INTRODUCTION

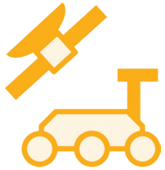
Data science enables the generation, fusion, and analysis of big data sets.

Missions increasingly rely on insights from big data sets. Analysis of engineering data informs spacecraft design and operations. In-situ analysis of environmental data enables autonomous navigation and decision making. Analysis of varied data types enables insights about interconnected systems, such as Earth's climate or star-forming regions.

JPL's existing data handling capability falls short of the magnitude of data that it currently collects. To manage, integrate, label, and analyze the unprecedented volumes of data gathered from multiple instruments, on ground and in space, JPL must advance data science research and applications.

ROLE IN SCIENTIFIC DISCOVERY

Data science provides the tools to generate scientific inferences while better quantifying uncertainties. Data-driven approaches applied to analysis-ready data can enable faster and more reliable scientific analysis. The incorporation of analytical workflows enables the efficient use of large volumes of varied data types. Robust statistical inference approaches enable the scaling of scientific analysis with big data. By integrating observational data with science models, scientists can create new data-driven modeling approaches across science disciplines. Earth science, planetary science, and astrophysics benefit from the automated analysis of large volumes of data on complex, interconnected systems.



BENEFIT TO JPL MISSIONS

Data science enables more efficient and productive design and operations. With advancements in data science, JPL receives deeper insights into system needs, behavior, and health, to improve anomaly detection and enable autonomous response. Data science further drives autonomy by providing the data infrastructure for AI/ML; automated labeling prepares big data sets for AI/ML more efficiently than manual labeling, saving time and operational costs. By increasing the efficiency of data storage and analysis, data science reduces power needs, which helps reduce overall mission costs. Finally, data science helps realize science mission outcomes with greater speed and clarity. For example, data fusion allows Earth science missions to combine new and historical data sets in areas such as weather, air quality, and hydrology, creating an interconnected view of Earth system changes over time.

Opposite: A future concept of interactive data systems to study asteroids and comets. Data science will increasingly allow scientists to analyze complex scientific data.

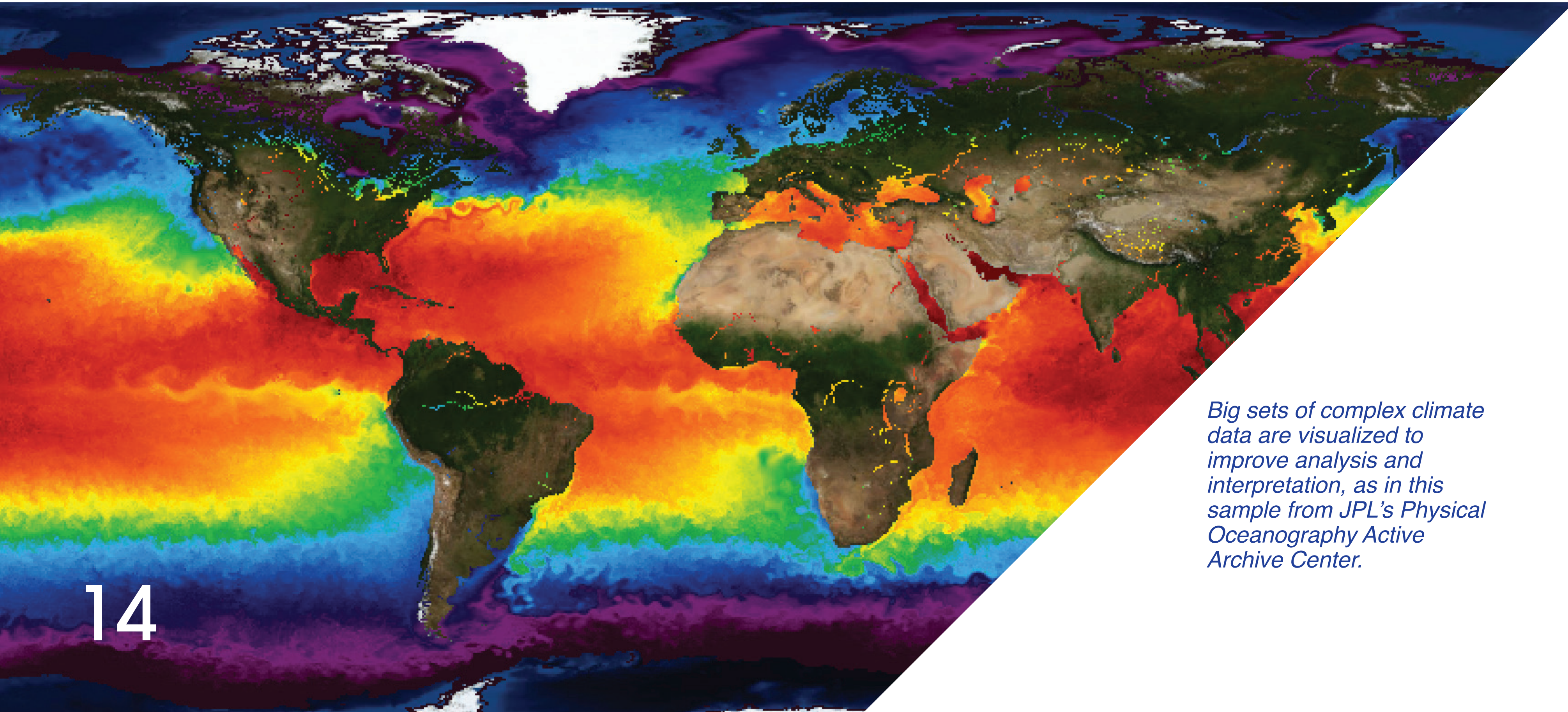
CHALLENGES

Data collection is outpacing data management and analysis. The volume and complexity of data returned by science missions continues to grow—at the scale of multiple terabytes. However, the data cannot be adequately managed and analyzed with current approaches to data infrastructure, computing processes, computing power, and data security.

The traditional approach to scaling data systems, increasing computation, is becoming untenable, for both ground and space operations. Data volumes and data variety overwhelm systems and humans, who spend more time preparing and labeling data than analyzing them. Attempts to make big data sets transparent and reproducible have met limitations in data archiving and concerns for data integrity and security. The data available for analysis are abundant but partially unusable without advances in data science.

SOLUTIONS

JPL addresses these challenges by advancing data science technology development in three areas: data management and compute-intensive architectures and ecosystems, data analytics, and uncertainty quantification. These areas are closely linked to AI/ML covered in Artificial Intelligence and Machine Learning.



Big sets of complex climate data are visualized to improve analysis and interpretation, as in this sample from JPL's Physical Oceanography Active Archive Center.

Data Management and Compute-Intensive Architectures and Ecosystems

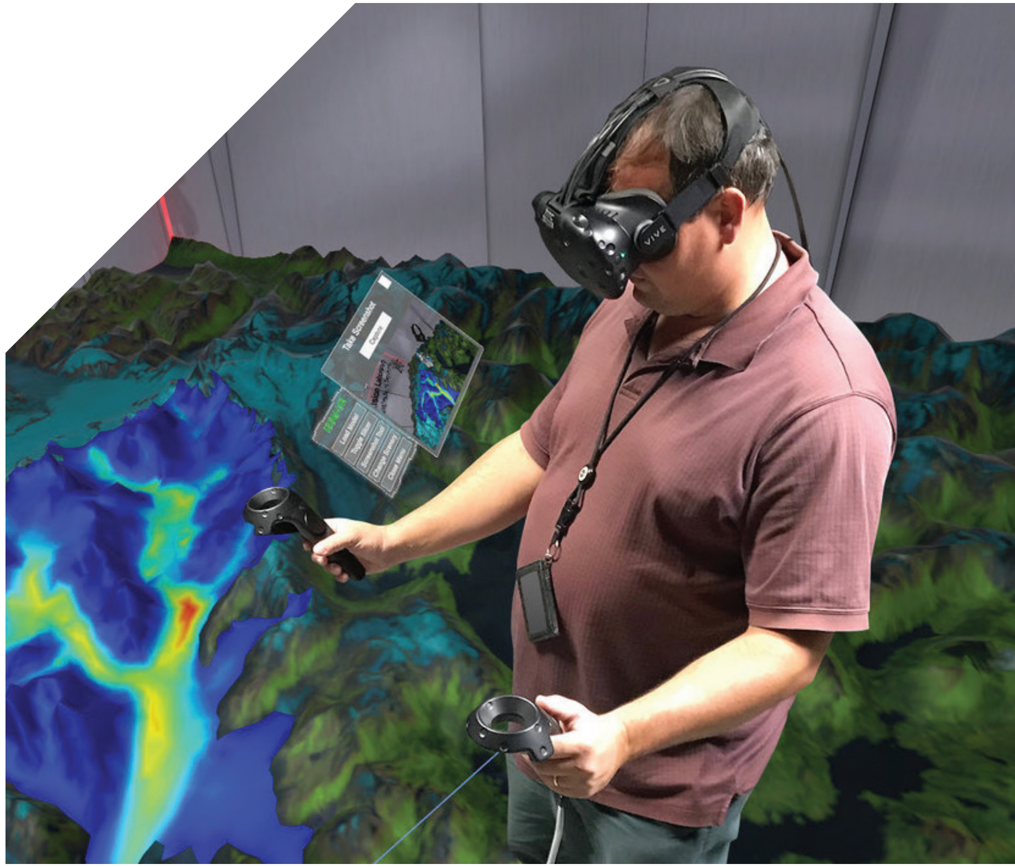
Data management and compute-intensive architectures and ecosystems enable systematic and autonomous approaches for capturing, managing, distributing, and analyzing raw information. Such architecture enables the use of machine-based intelligence at every stage to reduce raw data volume and efficiently extract information. Achieving this architecture requires advancements in data infrastructures, compute infrastructures, data models, and cybersecurity.

Data infrastructures enable scientists to meet real-time needs for cataloging, storing, retrieving, and searching exabyte data repositories. Catalogs using robust ontologies and information models help ensure that models drive data discovery. JPL needs new approaches for computation at the data site, support for data movement at the peta-scale level, and semantic associations between data.

Compute infrastructures such as neuromorphic and quantum computing support the scaling of data-driven methods. High-performance flight computing will be a critical enabler for both onboard analytics and autonomy. Areas to advance include hybrid computing, such as cloud and co-processors, and augmentations, such as cell phone processors or deep neural nets.

Data models manage diverse data types by explicitly defining data objects, enabling data analysis and discovery of unanticipated features. Advanced data models integrate machine learning methods that automatically tag and classify features in the data. Metrics for comparing the quality, accuracy, and variability of models must be developed along with computationally viable methods for evaluating the metrics.

Cybersecurity protects the integrity of JPL's data and algorithms. JPL needs data-driven methods for detecting security events in science and engineering operations data. Emerging protocol substrates, such as blockchain and other distributed ledger technologies, are potential areas for development.



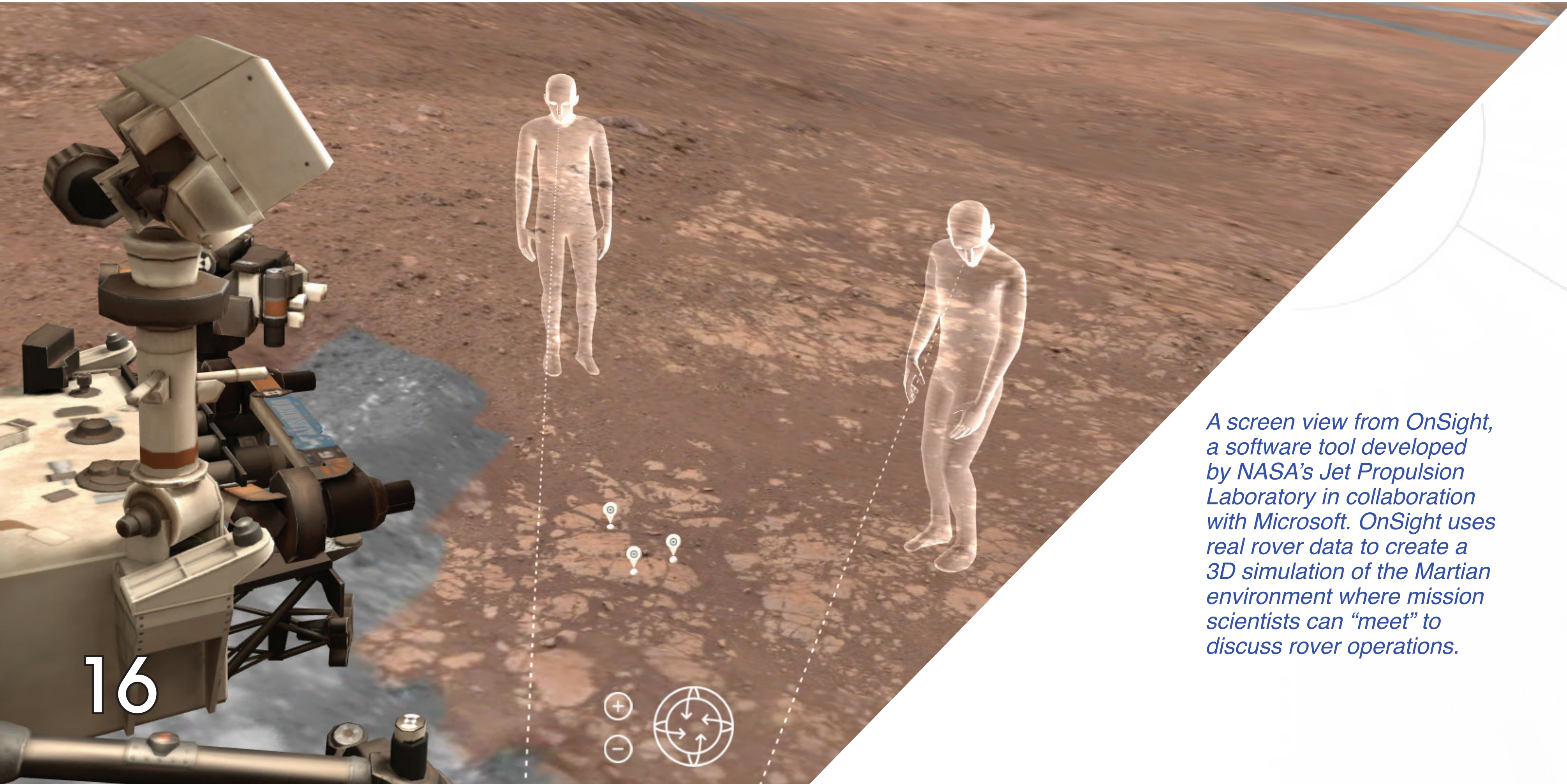
Virtual reality is allowing scientists to gain new perspectives on a rapidly changing planet. Here, Eric Larour explores Alaska's Columbia Glacier from his office at JPL.

Data Analytics

Data analytics systems and software examine and analyze data to extract meaningful insights. To mine and analyze increasingly large, noisy, and diverse data, JPL needs advancements in analysis-ready data environments and exploratory data analysis.

Analysis-ready data environments provide data that have already been prepared, allowing scientists to dedicate more time to analysis. To create analysis-ready data environments, JPL needs tools for efficiently creating labeled data sets. Amassing large data sets from different sectors to train ML models also support analysis-ready data environments.

Exploratory data analysis enables interactive analyses with the integration of scalable data infrastructures, on-demand data-driven computation and analysis, and visualization. New systems of interaction to advance include voice touch devices, intelligent digital assistants, 3D headsets, and other interactive visualization methodologies for automating and interacting with data.



A screen view from OnSight, a software tool developed by NASA's Jet Propulsion Laboratory in collaboration with Microsoft. OnSight uses real rover data to create a 3D simulation of the Martian environment where mission scientists can "meet" to discuss rover operations.

Uncertainty Quantification

Observations and models have uncertainties in how well a physical quantity or process is characterized. Uncertainty Quantification (UQ) provides a way to quantify the “value” of any particular sample by assessing the current physical understanding and existing observations. Understanding current uncertainties can quantify margins and inform the need for future observations, tests, or measurements. UQ techniques support formulation, engineering design and analysis, navigation and mission design, observation selection, science data analysis (including data fusion), and decision support. To advance UQ, JPL must advance surrogate models or emulators, model comparison, and observation selection beyond the current state of the art.

Surrogate models or emulators, such as neural networks, go beyond the traditional approach of addressing instrument measurement noise, by addressing the effects of algorithms, implementation, and models. Surrogate models run at significantly higher speeds than the full fidelity mode, and therefore better support standard Monte Carlo UQ experiments. With increased computing capacity, such as cloud computing, surrogate models can combine with higher fidelity models to increase accuracy in data fusion and scientific analysis.

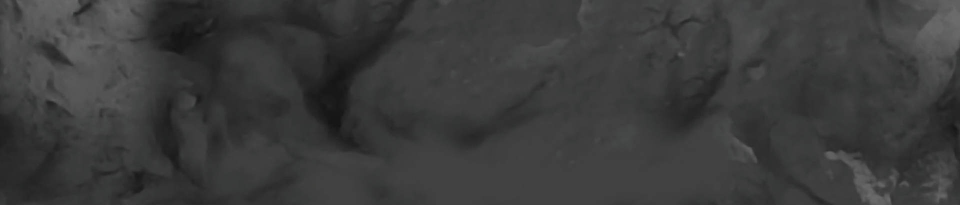
Model comparison builds trust in approximate models. Historically, the focus of scientific retrievals has been on estimating single-site errors. JPL must advance research to define and compute how one forward model approximates another model and to quantify the resulting model discrepancy for common retrieval types.

Observation selection uses AI/ML techniques to reduce uncertainty. Observation selection evaluates expected scientific return and determines where, when, what resolution, and what modality measurements to collect from a range of potential observations. JPL needs methods for aggregation, fusion, and assimilation that operate on wholly distributed sets of data, while still managing the propagation of uncertainties, to provide high-accuracy results with quantitative uncertainty and end-to-end traceability.

MINIATURIZED SYSTEMS

TINY MACHINES

MAXIMIZING THE POTENTIAL OF SMALL VOLUMES



INTRODUCTION

Miniaturized systems are fully integrated space systems with reduced weight, size, volume, and power consumption. Such systems enable missions previously considered cost-prohibitive and technically infeasible.

To realize these savings and enhanced capabilities, JPL will continue to focus on developing miniaturized systems at the component, subsystem, and system level. To function as a fully integrated miniaturized system, every aspect of the technology must survive the environmental challenges unique to space exploration.

ROLE IN SCIENTIFIC DISCOVERY

Miniaturized systems open new possibilities for exploration. Miniaturized spacecraft may take samples from Ceres, Pluto, or the moons of outer planets that were previously unattainable, while constellations of coordinated microspacecraft may provide inexpensive measurements to better understand Earth's systems. Shorter development times enable miniaturized systems to fly state-of-the-art technology, enhancing the volume and type of collected data. Coordinated miniaturized spacecraft enable coordinated measurements of interconnected systems, from those of Earth to those of star-forming regions.

BENEFIT TO JPL MISSIONS

Miniaturized systems reduce mission and launch costs, enable new capabilities, and accelerate development schedules. Miniaturization of components and systems is an ongoing process in space exploration. Since Cassini, imaging spectrometers have reduced size, weight, and power consumption by factors of 10 or more. Similar advances have occurred for other scientific instruments and spacecraft subsystems. With such reductions, JPL can increase the number of instruments per mission or pursue missions previously deemed cost-prohibitive.

Miniaturized systems can also increase the flexibility and adaptability of JPL missions, enabling new capabilities such as massively distributed sensing, and global networking, and the exploration of new destinations like planetary caves.

Opposite: Pop-Up Flat Folding Explorer Robot (PUFFER), developed at JPL, could be used as a scout for larger rovers, going places that would be risky or hard to reach.

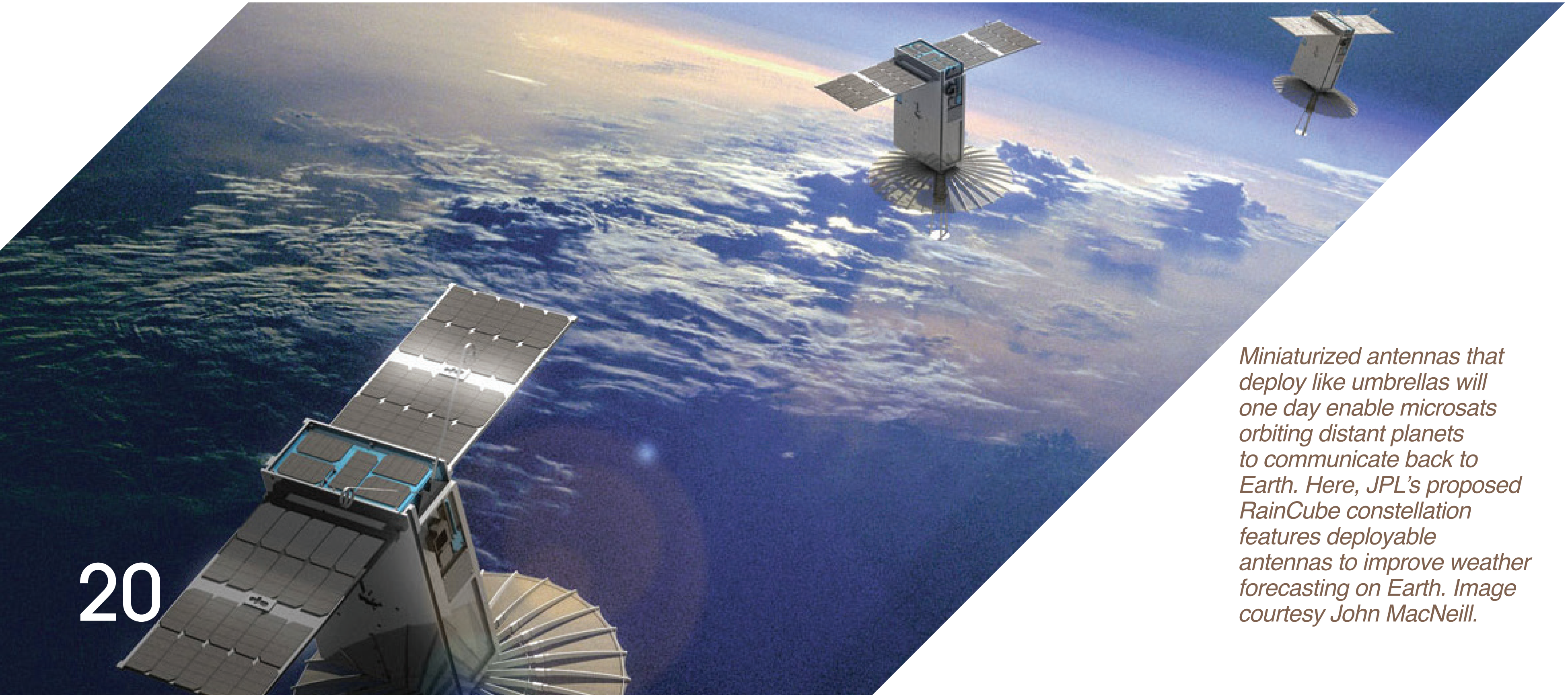
CHALLENGES

Because of the crosscutting benefits of miniaturization, advancements happen outside NASA as well. Although this external development presents a potential benefit to NASA, using commercial off-the-shelf (COTS) technology presents an integration challenge: all components and subsystems must withstand the radiation levels, extreme temperatures, and other environmental challenges of space environments. Qualifying these technologies for space use can add to a technology's mass and cost, offsetting the benefits of miniaturization.

Integrating new functionalities in miniaturized systems introduces other challenges. Higher performing computing systems can overheat a miniaturized system. Swarms of miniaturized systems, such as smallsats, demand extreme precision for navigation and communication. JPL must address these challenges without increasing the mass and cost of future missions.

SOLUTIONS

JPL addresses these challenges by advancing systems at the level of components, subsystems, and overall system integration. This technology will take advantage of advances in micro and nanotechnology to enable the next generation of insights and space systems.



Miniaturized antennas that deploy like umbrellas will one day enable microsats orbiting distant planets to communicate back to Earth. Here, JPL's proposed RainCube constellation features deployable antennas to improve weather forecasting on Earth. Image courtesy John MacNeill.

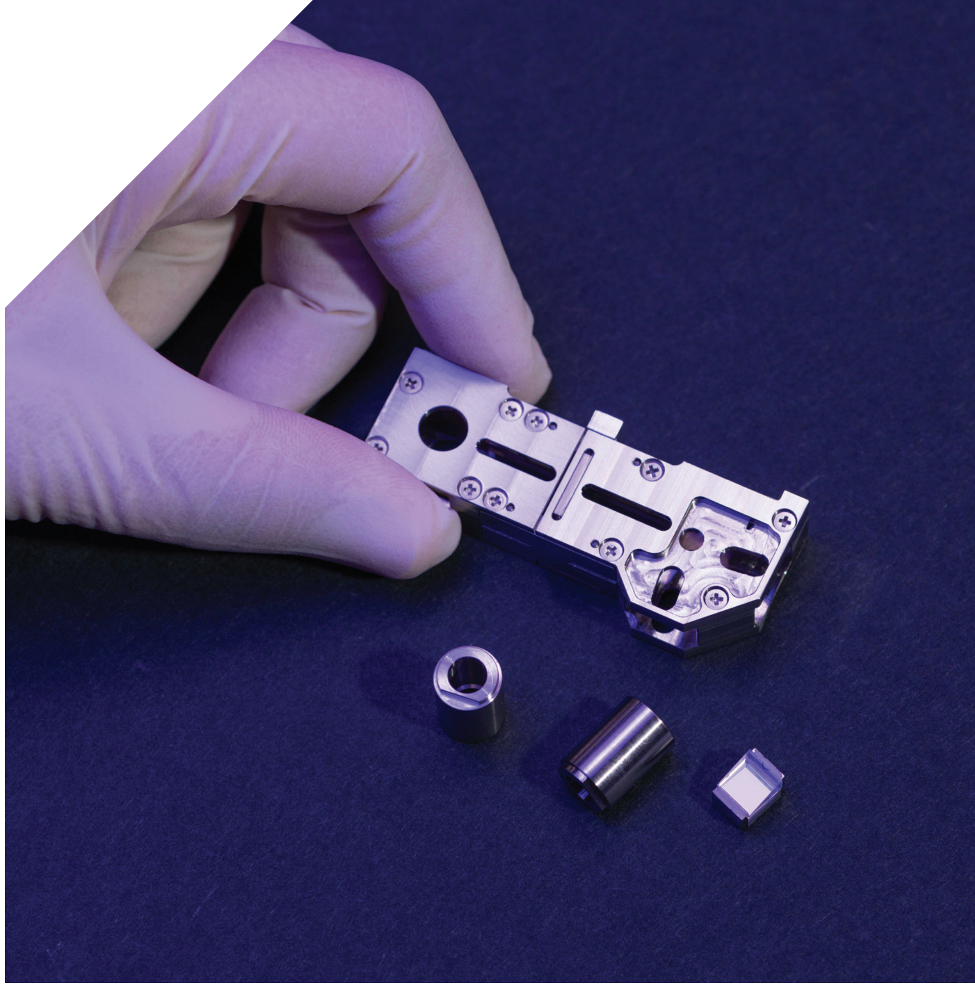
Nano and Micro Devices

For miniaturization at the component level, JPL must continue to develop space-compatible microelectromechanical systems (MEMS), applied nanotechnology, and integrated photonics beyond the current state of the art.

MEMS technology incorporates mechanical and sensing components in fabrication processes for microelectronics. To advance MEMS technology, JPL needs materials that can survive high levels of radiation and extreme temperatures. These materials can include III–V semiconductors, such as gallium nitride (GaN).

Applied nanotechnology involves manipulation of matter at nanometer dimensions for applications in materials or devices. One example application is photon-counting sensors, such as superconducting nanowire single photon detectors (SNSPDs). Using nano-scale patterning of thin-film superconductors, SNSPDs are high-performing detectors available over frequencies from ultraviolet to mid-infrared. Advancements in SNSPD arrays might enhance space telescopes pursuing exoplanet transit spectroscopy or space-to-ground quantum communications.

With integrated photonics, circuits use photons instead of electrons to perform different optical functions. One example is planar optical elements, which can enhance array performance across a wide wavelength range.



Miniaturized sensors, such as this high-resolution spectrometer developed at JPL, help realize bigger science in smaller, cheaper missions.

Subsystem Miniaturization

Miniaturizing subsystems involves qualifying COTS capabilities for the space environment and advancing microelectronic packaging technology.

Subsystems incorporating COTS capabilities can improve avionics and instruments by orders of magnitude and enable onboard autonomy. COTS capabilities to incorporate include neuromorphic processing, machine vision, graphics processing, and processor-in-memory architectures.

However, to incorporate COTS capabilities, JPL must mitigate the risks of radiation exposure. One mitigation strategy involves circuit-level architectures containing high levels of redundancy, which miniaturization makes more practical, and standard error detection and correction. Another mitigation strategy involves fabrication process modifications, known collectively as radiation-hard-by-design (RHBD). RHBD can yield long-life radiation-hard electronic and computing components that provide orders of magnitude increases in processing throughput, interconnect bandwidth, and memory capacities.

Microelectronic packaging involves miniaturized “system in a package” and “chiplet” technology. To develop quick turnaround, flexible, efficient, and space-qualifiable modules, JPL must advance chip-on-board technologies, slice-based designs for 3D stacking, and cold-capable electronics beyond the current state of the art.

System Miniaturization

For miniaturization at the systems level, JPL must take advantage of advances in smart materials and make use of technologies in several areas, including thermal, communication and navigation architectures, and multifunctional integration.

To survive the extreme hot and cold temperatures of space and planetary environments, and the higher heat load per volume of the spacecraft itself, miniaturized systems need new thermal management approaches. One approach is to incorporate thermally conductive planes at both the component and system levels to draw out excess heat. Another approach embeds active cooling loops, incorporating single-phase or more efficient two-phase thermal management systems into the structure. To survive cold temperatures, miniaturized systems need design architectures that provide efficient local heating when and where required.

Coordinated, or distributed, miniaturized systems need exquisitely precise timing for navigation and new communication approaches. Technologies to develop include chip-scale clocks and optical time transfers to synchronize clocks. JPL might also develop an architecture that incorporates WiFi or optical links to replace cabling between spacecraft components and subsystems.

Multifunctional integration is an architectural approach, often involving additively manufactured structures with multiple functions, such as thermal control, electronics and cabling, propulsion, and radiation shielding. Mass-saving designs include hybrid instruments, such as combined radars and radiometers, point and imaging spectrometers, and very wideband single instruments. Other mass-saving designs include combining spacecraft functions. For example, a deployable optical telescope might also be used as an RF antenna and thermal radiator. A deployable e-sail might double as a magnetoshell for both aerocapture and power generation once in orbit. These multifunctional mass and volume savings enable overall system miniaturization.

Opposite: JPL is working with various partners on Micro-Air Vehicle (MAV) that can be used for exploration of celestial bodies with atmospheres.

ADVANCED MANUFACTURING, DESIGN, AND MATERIALS

MAKING THE IMPOSSIBLE

MANUFACTURING ANYTHING FOR EVERYTHING

INTRODUCTION

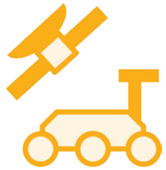
Advanced manufacturing, design, and materials (AMDM) uses new methodologies to design, analyze, and fabricate individual parts to entire systems of all sizes and complexity.

Traditional manufacturing approaches constrain the design of future missions. Advanced manufacturing, which includes additive manufacturing, also known as 3D printing, can efficiently produce advanced materials that meet performance requirements and mass restrictions. Advanced design methodologies also increase the possibilities for optimizing component and subsystem design. By integrating thermal, electric, optical, and other properties within one material, AMDM yields significant savings in system mass and mission cost. It also allows manufacturing of parts during a long-duration mission, a capability unimaginable before these advances.

ROLE IN SCIENTIFIC DISCOVERY

AMDM provides new capabilities and approaches for science experiments, technology development, and space exploration. Additive manufacturing allows scientists to customize and develop new concepts, such as a robust smallsat platform with all the elements for flight incorporated into its structure. Tailored materials and structures can increase the precision and sensitivity of scientific instruments, such as spectrometers and cameras.

New materials can be designed and printed to meet the needs of novel missions, such as mesh wheels capable of adapting to harsh extra-terrestrial terrains. Science return is increased further as efficient structures reduce mass and power consumption. These savings can then be used to improve or add instruments, introduce additional platforms, or generate new missions altogether.



BENEFIT TO JPL MISSIONS

AMDM enables new design approaches that lead to reduced mass and power consumption, thereby reducing mission cost. Additive manufacturing provides capabilities that reduce parts counts, shorten fabrication times, and reduce labor. AMDM also enables higher performing material composition options and more complex design spaces. It gives JPL the advantage of designing and producing a new class of measurement systems that can only be done by AMDM technology.

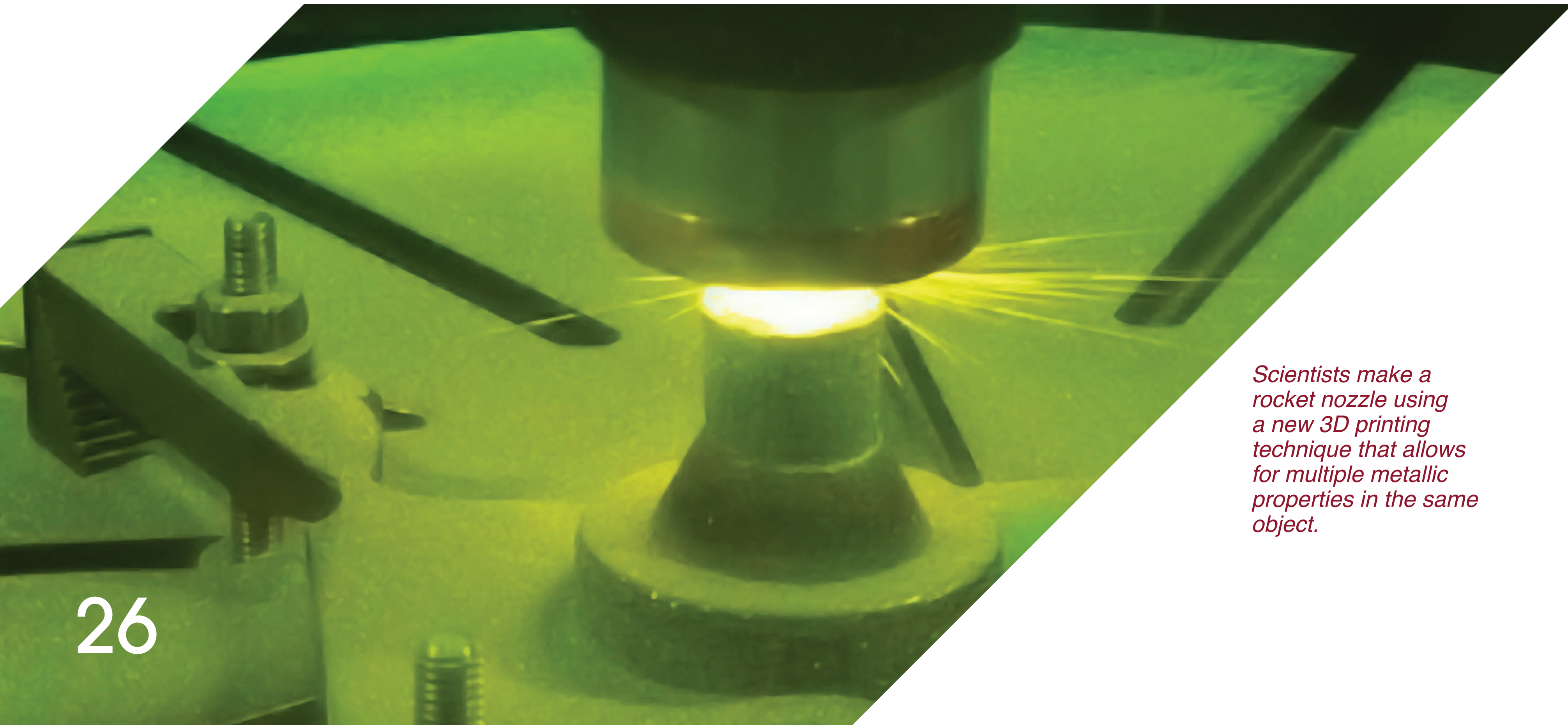
Opposite: Printing better radars—a novel application of additive manufacturing results in next-generation, complex microwave lens antennas that can provide beam scanning without moving parts.

Additive manufacturing is necessary for the production of multi-functional structures. Multi-functional structures act as primary, secondary, or non-loaded structures while providing additional mechanical, thermal management, electromagnetic, electrical, or actuation functionalities. For example, a smallsat could be manufactured with thermal control harnessing and micro-meteoroid protection integrated into its primary structure, or in-situ manufacturing of spare parts on a planetary surface could satisfy reliability requirements on long duration missions. Multi-functional space components produced in situ can enable significant savings in mass, power consumption, development costs, and operational costs.

CHALLENGES

The current state of AMDM faces limitations in computing capability and testing and integration challenges. Meanwhile, future missions need advancements in manufacturing, design, and materials to enable necessary mass and power savings without compromising overall performance.

The use of AMDM requires changes in computing capabilities and testing approaches. Advanced design addresses nonlinear optimization problems and builds intricate geometries, stressing the capabilities of current computer aided design (CAD) tools. To use advanced design, JPL must



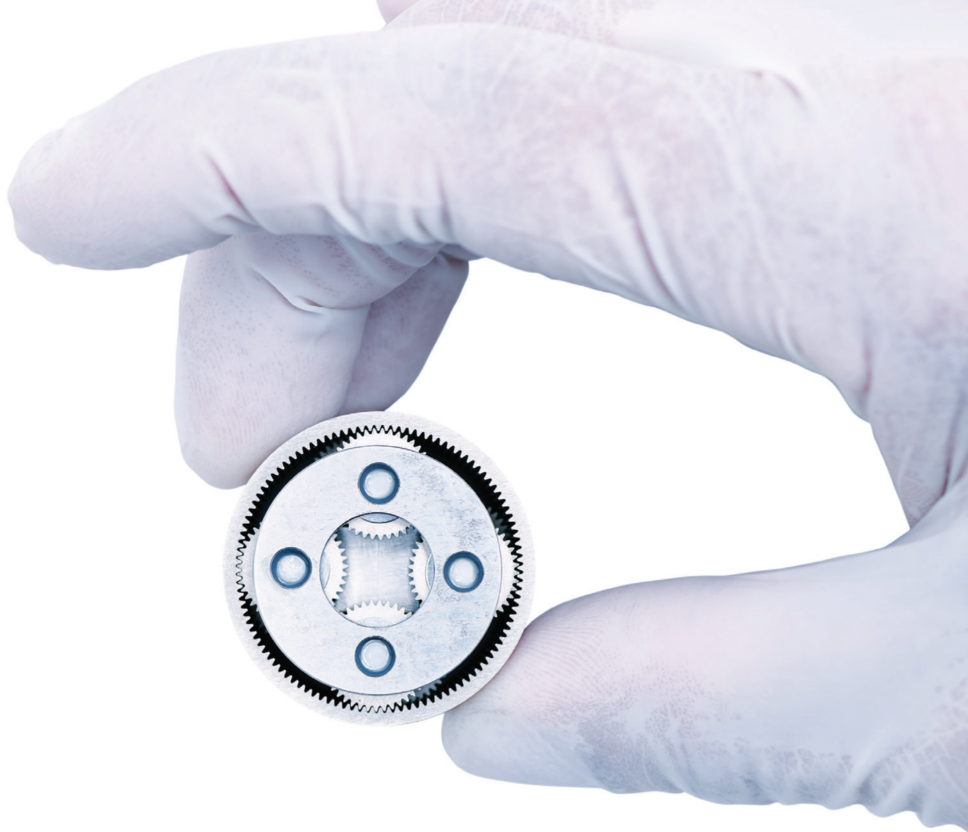
Scientists make a rocket nozzle using a new 3D printing technique that allows for multiple metallic properties in the same object.

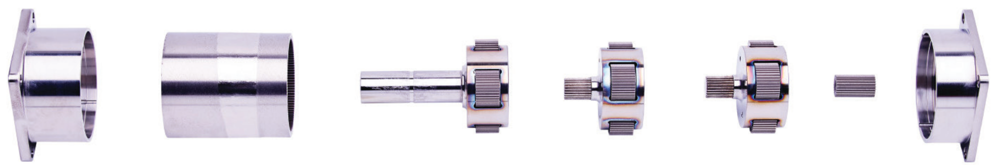
transition design tools onto high-performance platforms and restructure design tools to enable simultaneous processing on different systems. Components and systems developed with advanced manufacturing and materials cannot be tested the same way as traditionally developed components and systems. To test anything made with advanced manufacturing and materials, JPL needs new verification and validation (V&V) approaches and qualification methodologies. Ultimately, as modeling, design, and analysis tools become more integrated, JPL must move from a mainly serial process, consisting of islands of locally optimized components and subsystems, to an integrated system-level approach.

Future mission architectures demand more science capability per mass than traditional manufacturing, design, and materials can achieve. Distributed systems of miniaturized spacecraft and vehicles for surface exploration must reduce overall mass and power consumption. However, these systems must also posses the durability necessary for surviving in space and planetary environments, including resistance to radiation exposure, extreme hot and cold temperatures, abrasive surfaces, and corrosive liquids. Traditional manufacturing, design, and materials cannot provide high-performing capability without increasing overall mass and power consumption.

SOLUTIONS

JPL addresses these challenges by developing smart materials and advanced design and analysis. These advancements enable the development of miniaturized systems, discussed in Miniaturized Systems.





Advanced materials make space systems simpler and more reliable. A bulk metallic glass gear (pictured here in component parts and as a complete system) can operate without liquid lubricant, an improvement for future NASA missions.

Smart Materials

Advanced manufacturing processes create structures, subassemblies, assemblies, and systems that are impossible to fabricate with conventional methods. Areas to develop include hybrid manufacturing methods, multi-material printing, and tailoring of material properties.

Hybrid manufacturing combines different production techniques to create a single part while maintaining control of all involved elements. Hybrid manufacturing includes techniques such as multi-scale printing, which can print structures from meter to nanometer scale within a single part. Another technique is component embedding, in which pre-built electronics, sensors, or actuators are assembled into a part during additive manufacturing production. These techniques increase the complexity of geometries and precision possible with additive manufacturing.

Multi-material printing combines different materials to form a single printed part. One example is gradient alloy printing, which seamlessly transitions from one metal type to another. By tailoring a system's structural, thermal, electrical, or radio frequency properties, multi-material printing can help increase system performance. For example, multi-material printing can create embedded sensors for system health assessment for onboard autonomy and "smart materials," such as joints printed with shaped memory alloys that can serve as integrated actuators.

Additive manufacturing also enables the tailoring of alloy properties to optimize high-performing characteristics. For example, the favorable ferromagnetic properties of an iron-cobalt alloy can apply to magnetically shielded Hall thrusters, high-efficiency motors, and low-loss power systems. High-entropy alloys, such as multi-principal element alloys (MPEAs) and complex concentrated alloys (CCAs), are areas for further development. MPEAs offer a vast composition space, with structural and functional materials applications. CCAs involve materials with metallic, ionic, and covalent bonding and microstructures with different material phases. These areas for development offer improvements in complex compositions and microstructures.

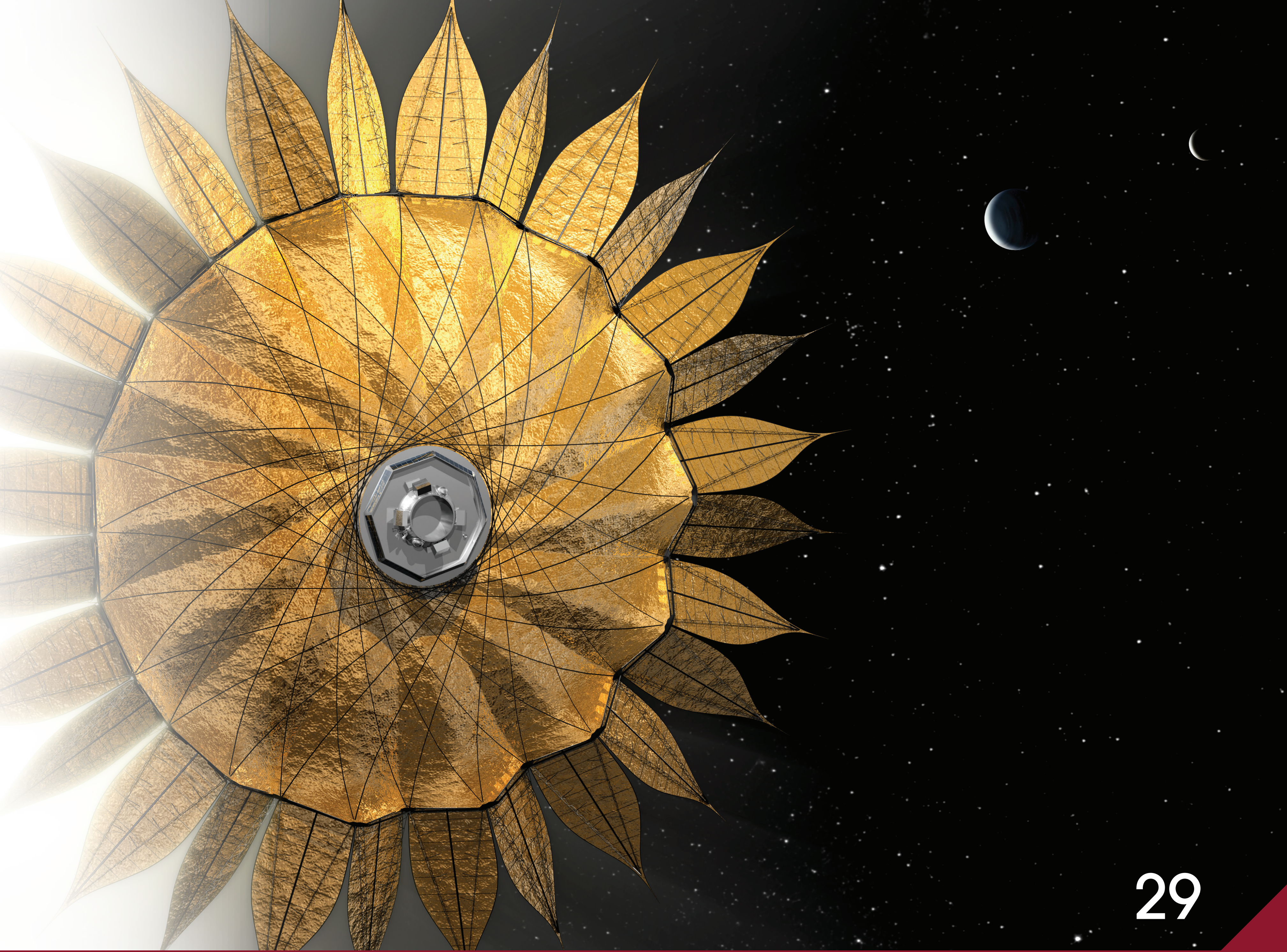
Advanced Design and Analysis

Advanced design and analysis methods and tools enable computational design of materials for optimal performance.

One design and analysis method to develop is topology optimization. Topology optimization is a mathematical framework to computationally design a structure for optimal performance based on relevant constraints and loading conditions. For example, if a structure needs improvements in thermal properties, the framework accounts for design domain, performance requirements, boundary conditions, and loading environments.

New design and analysis methods require increased design tool capability. Areas for development include multi-physics modeling and simulation, such as heat transfer, radio frequency, optical, and electronics, and tools for concurrent and nonlinear design optimization.

Opposite: Scientists can launch structures of unprecedented size and capability by developing small structures that can be deployed or assembled into large structures once in space. The deployable StarShade concept will require deployment to millimeter accuracy as well as development of specialty materials that are flexible, precise, lightweight, and resilient.



DISTRIBUTED SYSTEMS

SWARM POWER

BIG RETURNS USING SMALL LINKED MACHINES

INTRODUCTION

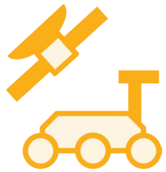
A distributed system is a coordinated group of assets, including satellites, telescopes, antennas, and vehicles. A distributed system can involve as little as two and as many as thousands of individual assets.

The flexible size, movement, and increased redundancy of distributed systems significantly increase opportunities for different scientific measurements. To reach these opportunities, JPL must develop methodologies and synchronization technologies that enable a distributed system.

ROLE IN SCIENTIFIC DISCOVERY

Distributed systems enable scientific measurements that are not possible with one monolithic spacecraft. The individual assets of a distributed system can simultaneously measure a dynamic science target from different perspectives, enabling more detailed cloud tomography and higher resolution stellar interferometry, for example. Distributed systems also enable spatially diverse transmitter and receiver placements; for example, multistatic radar for enhanced tracking or density measurements becomes possible. A distributed system of planetary explorers can construct a fused map of an environment. Meanwhile, a distributed system of formation flyers can emulate a structure, such as a large aperture for imaging exoplanets or studying galaxy formation, that would otherwise be too large for a conventional launch vehicle. A swarm of distributed systems can reconfigure to accomplish multiple measurement goals.

With increases in spatial and temporal coverage, accessibility of high-risk targets, and perspectives for measurement and imaging, distributed systems have applications in Earth science, planetary science, and astrophysics.



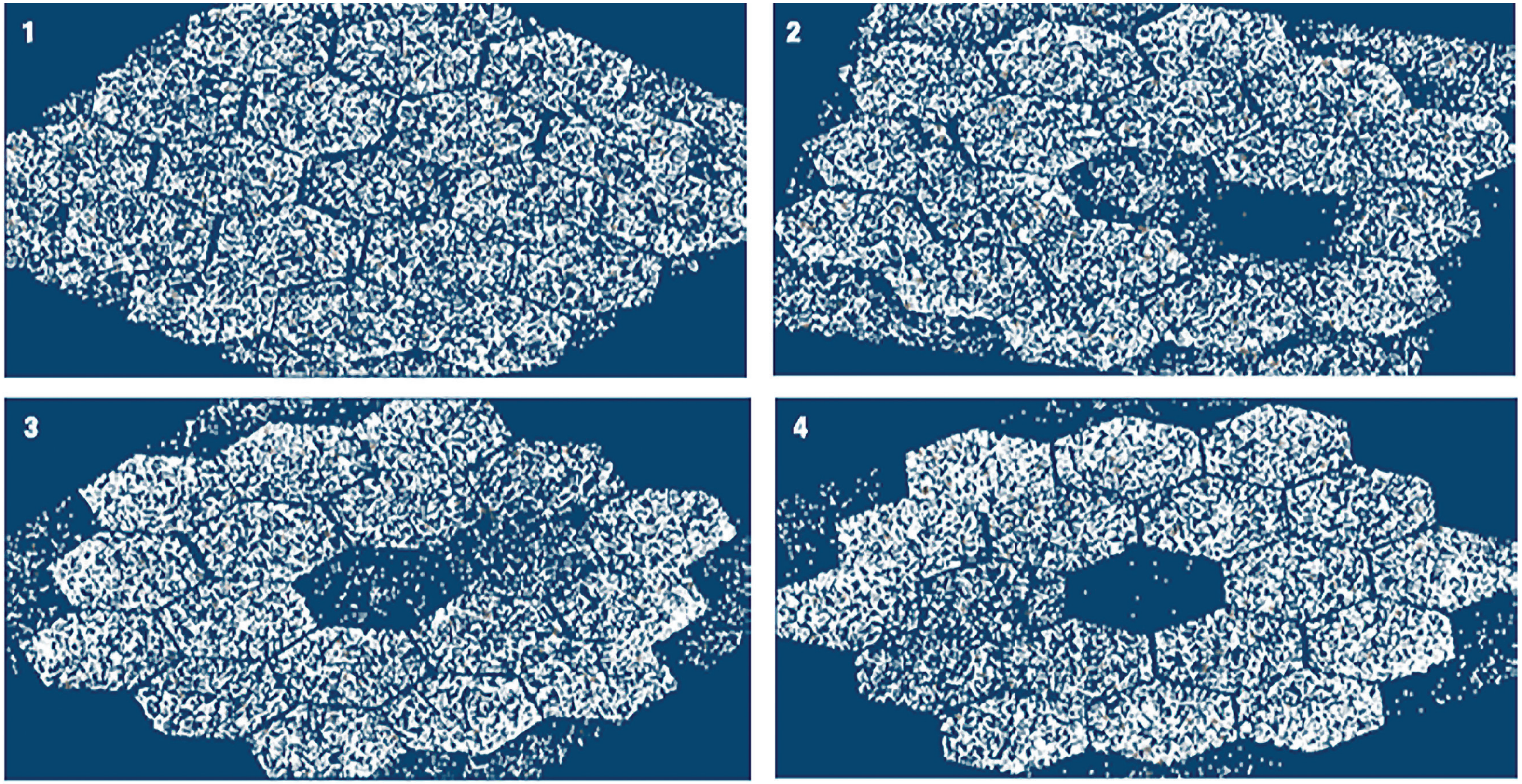
BENEFIT TO JPL MISSIONS

In addition to increasing the possibilities for scientific measurements, distributed systems enable JPL missions to accept higher risk postures for individual assets. A distributed system of smaller and less expensive assets provides more redundancy than a single spacecraft. With greater risk tolerance, JPL missions can explore high-risk scientific targets, such as cliff edges, cave interiors, lava tubes, crevasses, and comet comas. Furthermore, most distributed systems involve autonomous and miniaturized systems and therefore provide lower operational, manufacturing, and mission cost due to reductions in size, weight, volume, and power consumption.

Opposite: An artist's rendering of a notional mission composed of telescopes in a distributed system orbiting far from the Earth-Moon system.

CHALLENGES

To image exoplanets or continuously monitor a phenomenon, distributed systems require precise networking of fully autonomous assets. To navigate in uncertain environments, avoid collision, reconfigure to compensate for a disruptive event, or reconfigure to optimize a measurement, each agent in a distributed system must individually sense, analyze, and plan and execute decisions while also in real time communicating and coordinating with the other assets in the system. To create, maintain, and change orientation, to form swarms or large apertures, precise relative position control will be required among all coordinating assets. Each asset must also have a precise timing capability to ensure synchronization.



A swarm of distributed systems can provide great benefit for space missions because of their ability to adapt to changing environments. Here, a simulation demonstrates how thousands of femtosats could reconfigure following a disruption.

SOLUTIONS

To address these challenges, JPL must develop technologies and methodologies that enable three areas of multi-spacecraft applications including: networked distributed systems, precision synthetic apertures, and swarms. Every chapter of this report describes at least one technology area that enables distributed systems to some extent.

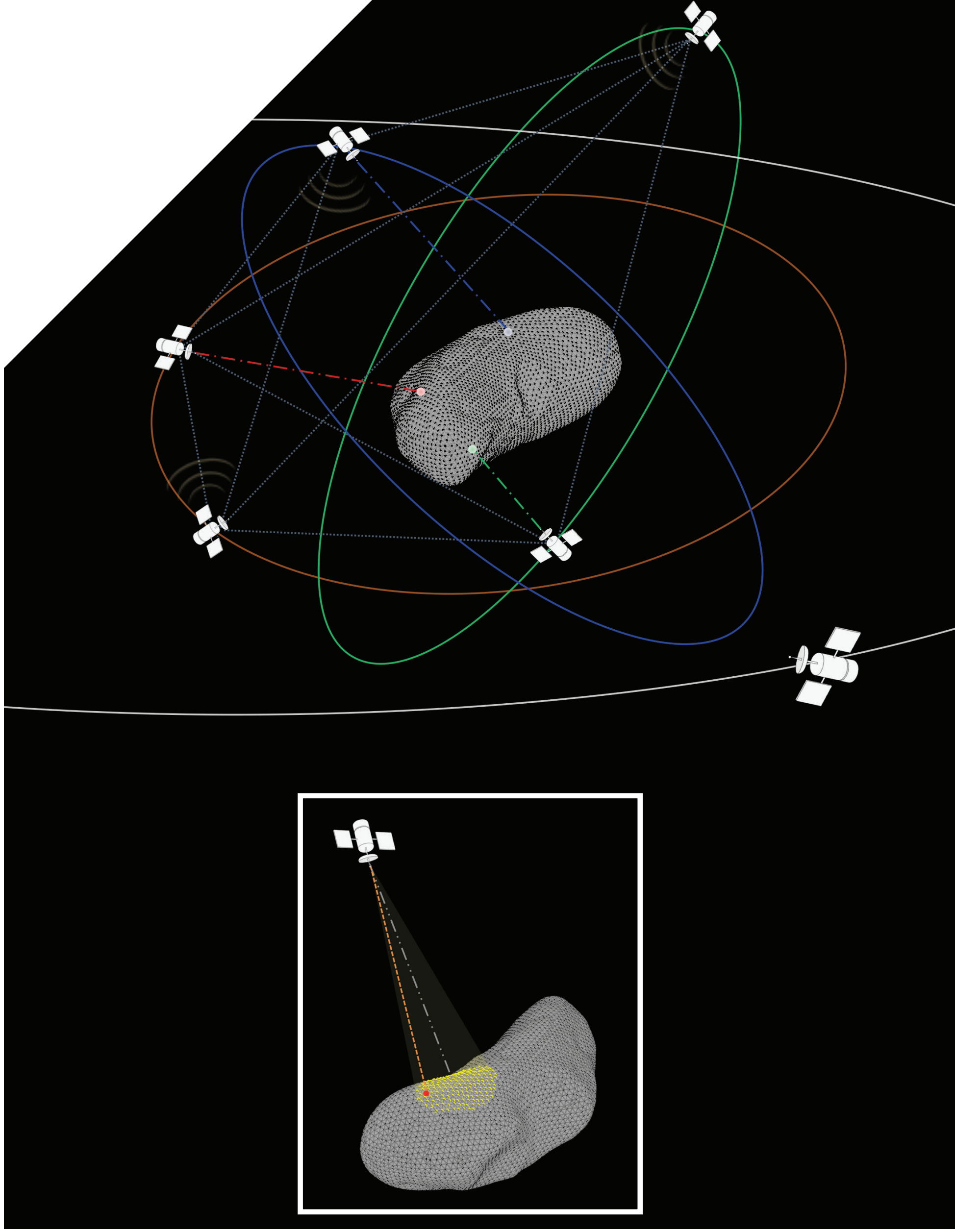
Networked Distributed Systems

A networked distributed system (NDS) is a group of virtually connected cooperating assets. To enable an NDS, JPL needs advancements in relative sensing and control, collective decision-making, thrusters, and data integration and fusion.

Relative sensing and control enables the assets of an NDS to simultaneously map a new environment, ascertain their own positions in that environment, and communicate this information to the other assets in the network. An NDS needs this capability for collision avoidance in space and to explore unmapped terrain. This capability requires algorithmic computational frameworks that can establish and maintain the NDS in uncertain situations and scenarios.

Collective decision-making increases the robustness of an NDS by accounting for potential occlusion, interference, or latent communication within the multi-asset system. Areas to develop further include graceful degradation and fault detection, identification, and recovery (FDIR) approaches.

NDSs in free-flying formations need advanced thrusters to change or maintain relative positions. These thrusters must be fuel-efficient to account for the net changes in velocity involved in moving or stabilizing a multi-asset formation. These new thrusters must also achieve a large dynamic range, from fine impulse control for configuration station-



Swarms of satellites can enable a complex picture of dynamic exploration targets. Here, a swarm of integrated satellites image an asteroid in great detail. Inset, a single satellite is much less capable of developing the complex imaging needed for asteroid exploration.

keeping to larger impulses for agility and reconfiguration. Other considerations include a narrow exhaust cone to mitigate effects on neighboring assets.

Whether in space or on a surface, NDSs require different approaches to integration and fusion of sensor data. Some network scenarios require centralized control using distributed sensor information. Other network scenarios require decentralized control using biomimetic algorithms. Regardless of the control architecture, all NDS assets must incorporate scalable, multi-objective, six-degrees-of-freedom (6DOF) constrained path planning relative to other assets and, when applicable, relative to the terrain.

Precision Synthetic Apertures

A distributed system of precision synthetic apertures enables higher resolution and more efficient space-based interferometry. Instead of a very large monolithic space system, distributed space-based interferometry uses two or more apertures—either telescopes or antennas—to achieve subarcsecond resolution at infrared and far-infrared wavelengths. Rather than detect exoplanets as dots of light, a distributed system of apertures enables multi-pixel imaging, revealing details of an exoplanet's surface and weather. With more antennas in the system, the imaging becomes more precise, but the implementation becomes more challenging. To address the challenges of implementing a distributed system of precision synthetic apertures, JPL must develop technologies to enable new configurations, such as planar arrays or spherical arrays.

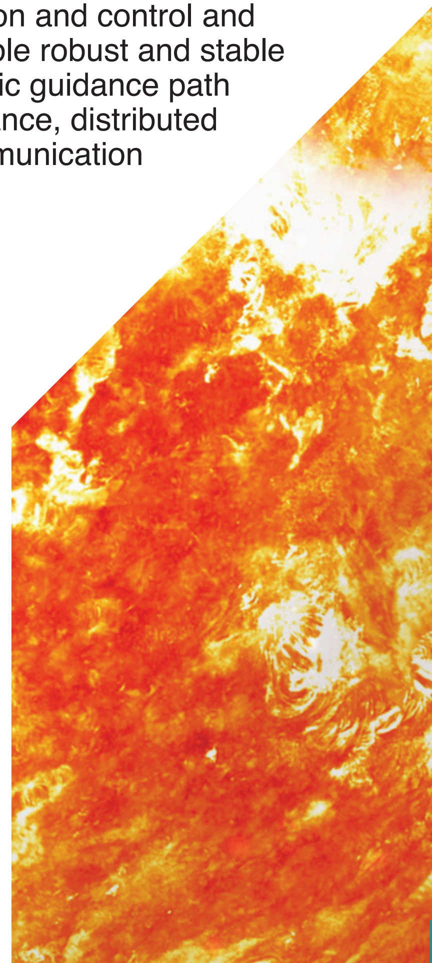
A planar array involves 10 to 100 spacecraft in a region of approximately 1 kilometer. To reorient the array, each spacecraft needs a very-low-thrust propulsion system with close-to-perfect on/off ratios. To ensure the needed centimeter-scale precision of the spacecraft spacing, JPL needs advancements in autonomous coordination, sensing, and chip-scale clocks for precise timing. Advances in absolute and relative precision metrology systems along with onboard real time control will be needed to achieve desirable shape and system level positioning control of the entire array.

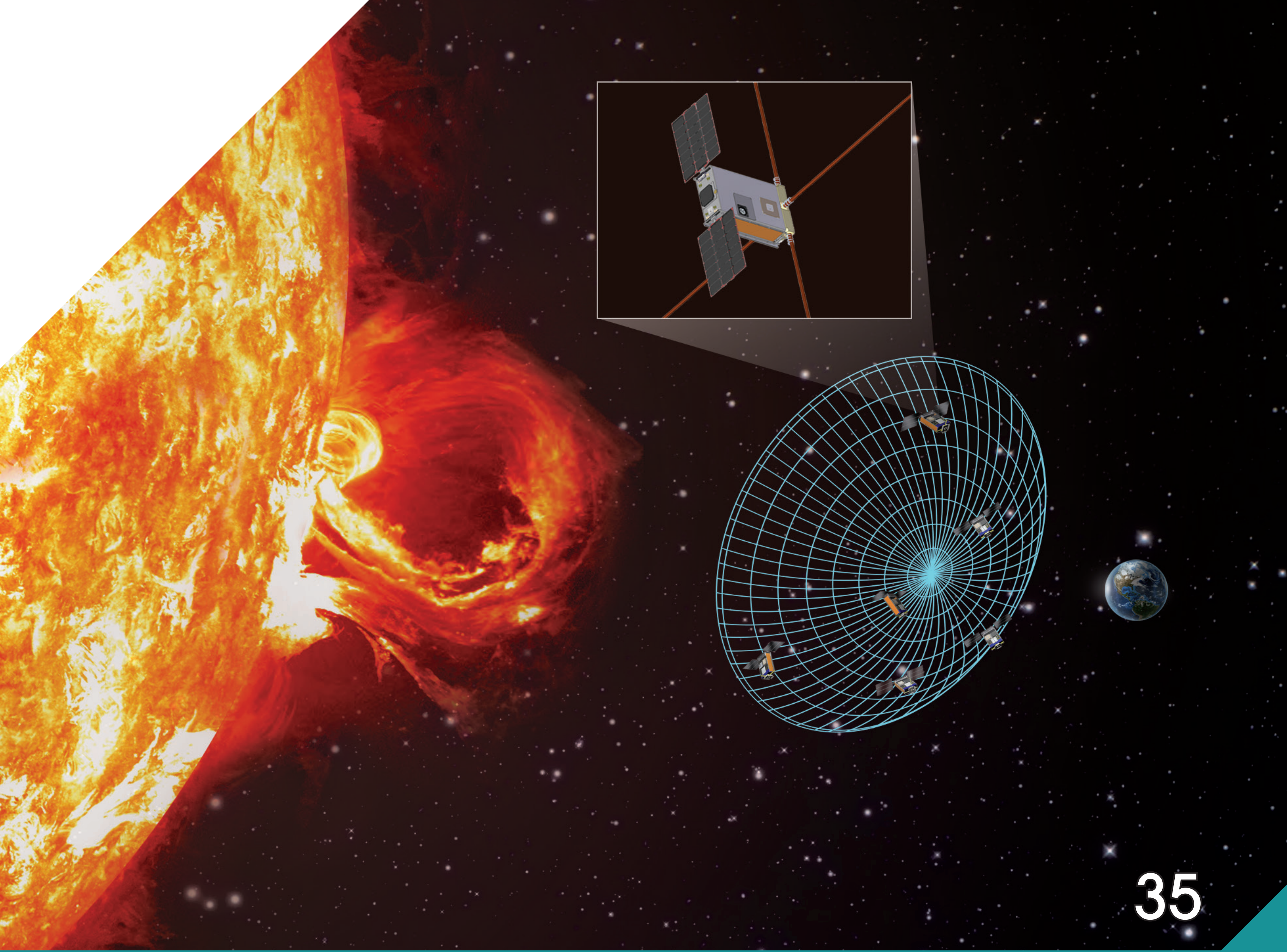
Swarms

Swarms of distributed systems enable statistical analysis of individual viewpoints. This statistical analysis then builds a collective picture of each asset's surroundings.

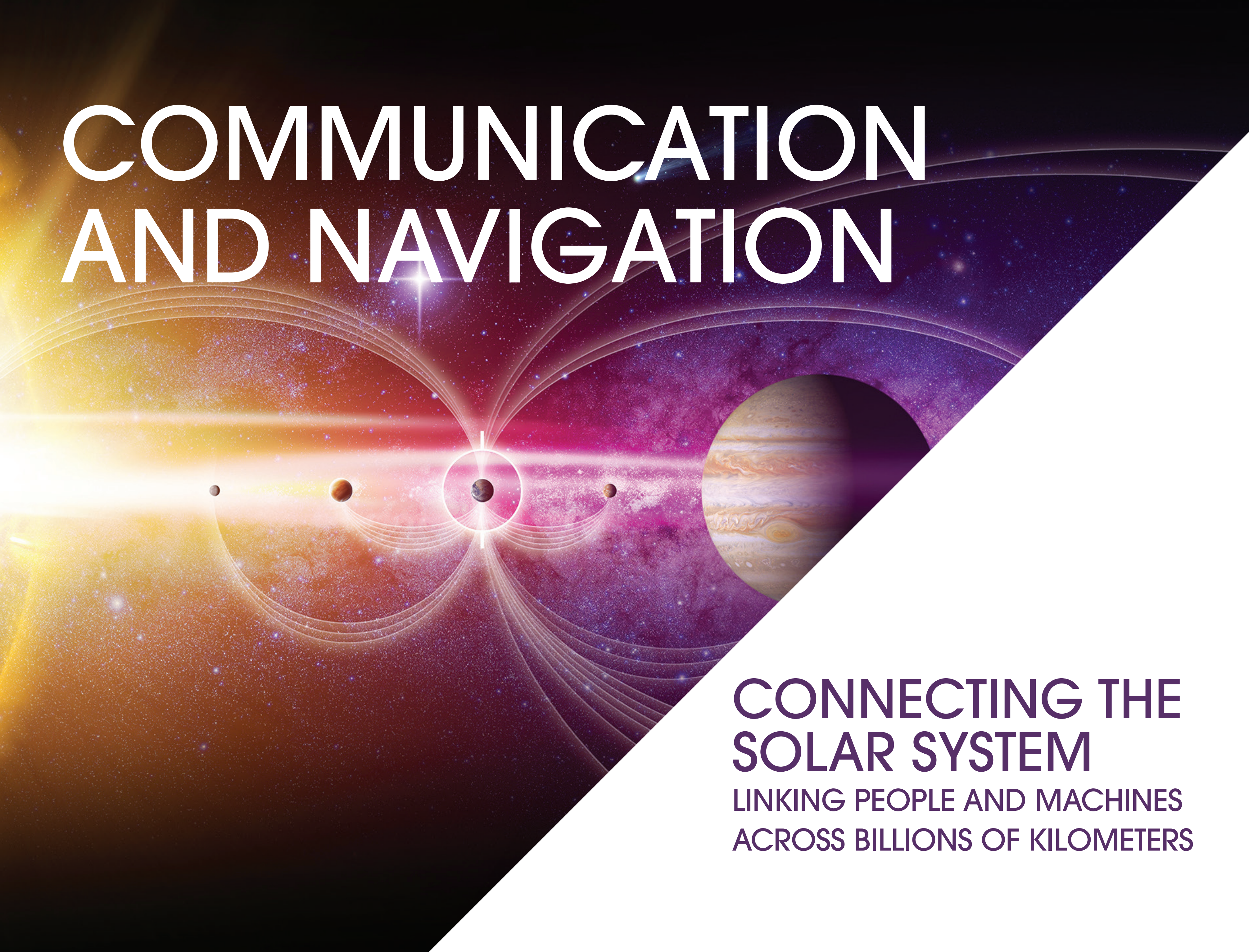
Statistical analysis also enables the swarm's functions. Swarms require stochastic coordination and control and massively sensed estimation. To enable robust and stable swarms systems, distributed stochastic guidance path planning, probabilistic collision avoidance, distributed state estimation, and distributed communication technologies will be needed.

Constellations of distributed satellites operating together can mimic the power of an antenna, mirror, or sensor that would need to be much larger—likely too big to launch. Here, the Sun Radio Interferometer Space Experiment (SunRISE) would coordinate CubeSats in formation to operate as a synthetic aperture radio telescope to study solar energetic particles.





COMMUNICATION AND NAVIGATION



CONNECTING THE SOLAR SYSTEM

LINKING PEOPLE AND MACHINES ACROSS BILLIONS OF KILOMETERS

INTRODUCTION

Communication and navigation connect space missions to ground operations and map spacecraft trajectories. Here, navigation includes position determination and onboard path planning.

As missions extend farther and operations become more complex, communication and navigation must become more robust, accurate, efficient, and autonomous. By mitigating delays and data loss, reducing planning time and fuel consumption, increasing data rates, and reducing user burden for communications in mass and power, advances in communication and navigation yield benefits on the ground and in space for every mission.

ROLE IN SCIENTIFIC DISCOVERY

With advanced communication and navigation technologies, science missions can reach new targets and send more data back to Earth. Spacecraft use low-energy trajectory designs to explore new, once inaccessible locations. Enhanced communication enables coordination among distributed assets, making new missions and scientific measurements possible. Optical communications increase data rates by a factor of 10 or more, enabling progressively more difficult missions and more precise measurements.

BENEFIT TO JPL MISSIONS

Advancements in communication and navigation mitigate data loss, reduce mission cost, and enable new mission types. New communication protocols accommodate delays and potential disruptions, enabling more robust data transmissions and larger data volumes across the entire solar system. These protocols also automate relay functions, thereby simplifying operations and reducing associated costs. In navigation, low-energy trajectory designs minimize propellant needs, also reducing mission cost. New approaches to communication and navigation also enable exploration with multiple distributed assets and exploration of multiple targets per mission.

Opposite: JPL is developing advanced communications and navigation systems enabling enhanced exploration of the entire solar system and interstellar space.

CHALLENGES

Current communication and navigation technologies do not offer enough capacity or robustness for future missions. Increasingly precise and complex science questions demand higher data rates. Deep-space and high-data-rate applications need more powerful transmitters.

The risk of communication delays and disruptions increases as the distance and complexity of a mission increases. Current communication protocols, such as those for terrestrial internet, require continuous data exchange, with little to no delays or disruptions. To travel farther and conduct complex missions, spacecraft need communication protocols that can mitigate or accommodate delays and disruptions.

With current navigation approaches, mission design involves time-consuming trajectory analysis that prolongs mission planning. Current navigation approaches also lack the accuracy and positioning system needed for feasible deep-space trajectories.

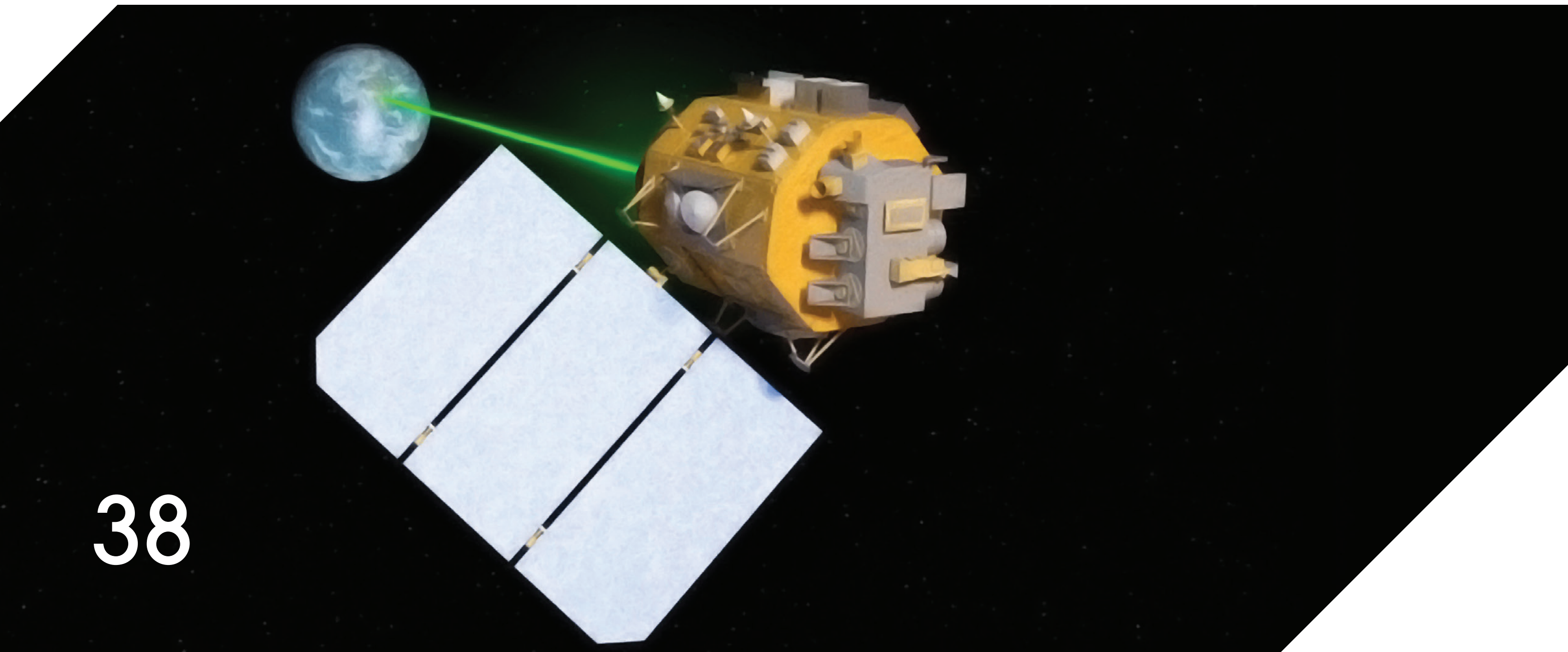
SOLUTIONS

To advance communication and navigation for use in deep space and autonomous operations, JPL needs technology development in radio frequency (RF) and optical communications, disruption tolerant networks (DTNs), and navigation and mission design. These solutions contribute to the exploratory systems described in Autonomous Systems and Distributed Systems.

RF and Optical Communications

Optical communication augments RF to increase data rates. To increase data rates while reducing size, weight, power, and cost, JPL must advance power amplifiers, telescopes and detectors for optical frequencies, and quantum technology beyond the current state of the art.

RF communication requires high-efficiency Ka-band power amplifiers for both flight and ground transmitters. For flight transmitters, GaN-based amplifiers must be extended for use



Several upcoming NASA missions will use lasers to increase data transmission from space.

at the Ka-band power level. For ground transmitters, arrayable Ka-band amplifiers can meet the increased power demands. Uplink arraying requires efficient and automated coherent combining with adaptation for atmospheric correction.

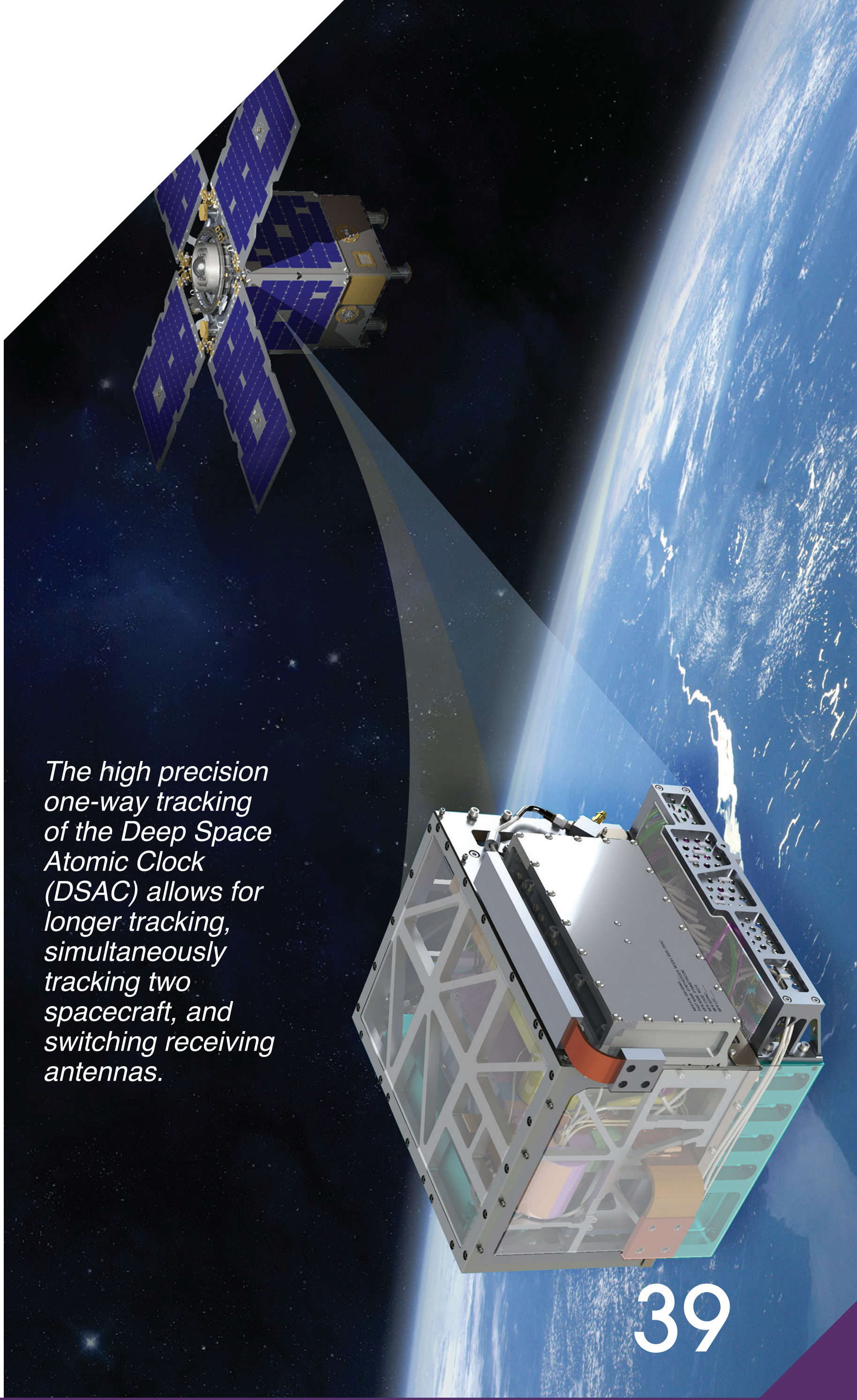
Power amplifiers at optical frequencies increase the output power for optical communication transmitters. JPL can use photonic integrated circuits to reduce the size and increase the transmitter reliability of onboard transmitters. Arrays of high-power laser transmitters, arrayed telescopes, and innovative signal structures can increase modulation while reducing power consumption. For onboard signal detection, JPL needs high-efficiency, large-format photon-counting detector arrays with fast readouts that advance the current state of the art.

The shift to optical frequencies requires advancements in telescopes and detectors. Pointing, acquisition, and tracking (PAT) technologies can address the narrow optical beamwidths. JPL needs flight optical telescopes with larger effective apertures (50 cm or more) but lower mass. For ground receiving telescopes, JPL can use large apertures (12 m or larger), using cost-effective approaches such as fabrication with additive manufacturing or synchronized arrays.

Quantum technology can expand transmission capacity and improve communication security. Quantum communication can significantly improve channel capacity. Quantum key distribution provides unconditional security.

Disruption Tolerant Networks

DTNs use store-and-forward networking to support the deployment of a Solar System Internet. The core DTN protocols have been defined and fully standardized to enable interoperability across space agency missions. As JPL continues to develop these protocols, JPL must incorporate DTN in mission architectures.



The high precision one-way tracking of the Deep Space Atomic Clock (DSAC) allows for longer tracking, simultaneously tracking two spacecraft, and switching receiving antennas.

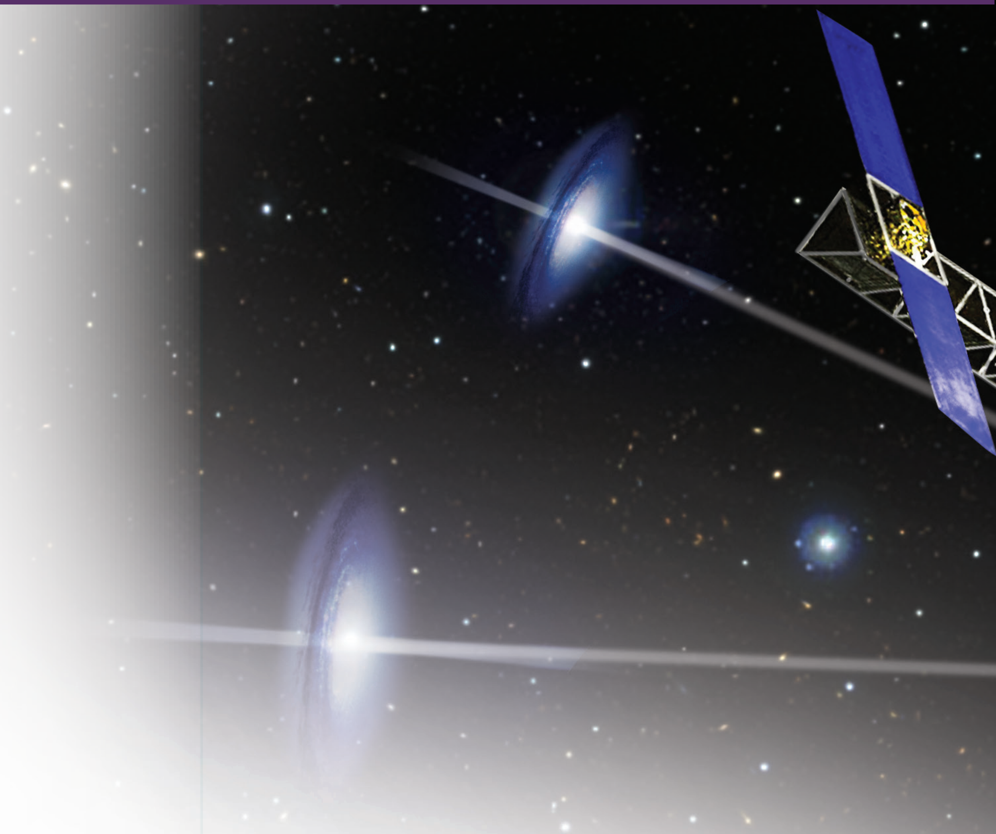
To complete the DTN protocol suite, JPL must develop routing algorithms that work in concert with onboard software. The addition of these algorithms enables autonomous coordination and data return among a network of nodes in deep space. Additional areas to enhance for DTN development include security, network management, routing, and quality of service.

Navigation and Mission Design

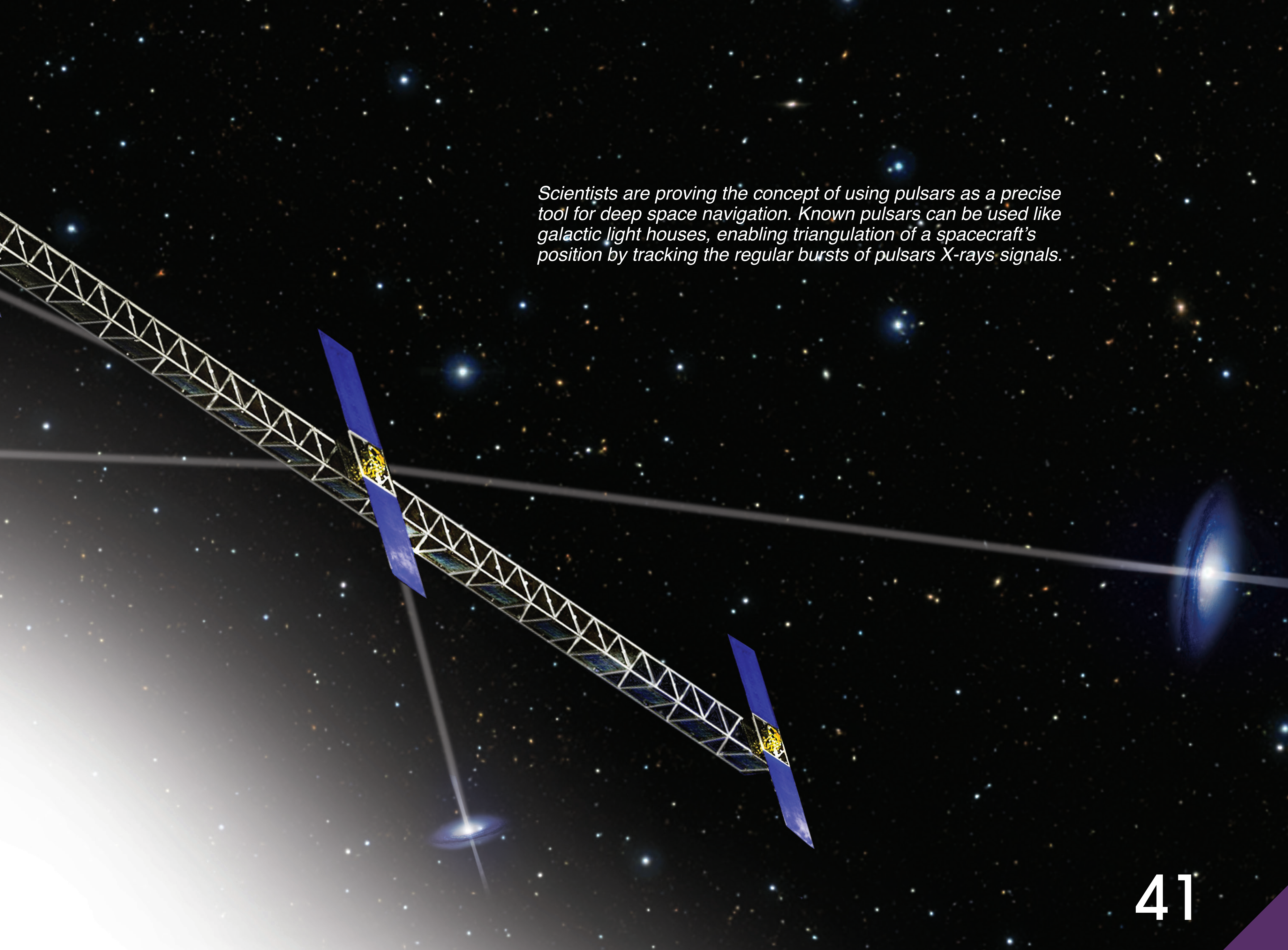
Navigation and mission design technologies find and optimize trajectories to efficiently reach desired destinations. For example, the use of massively parallel algorithms determines the long-term stability of planetary system orbits that minimize launch vehicle and spacecraft propellant needs while also meeting planetary protection requirements. To expand on these technologies, JPL must advance dynamical solar system models, optical ranging, and deep space positioning.

Dynamical system models of solar system gravitational fields optimize low-energy trajectories and multi-body tours. JPL must develop methods that reduce the analysis time to find tours or classes of tours for missions with a variety of characteristics, including chemical propulsion, low-thrust continuous propulsion, hybrid systems, and multi-asset systems. These methodologies must also incorporate pointing and environmental constraints, such as total radiation dose, and quantify trajectory uncertainties for long-duration interplanetary missions.

An optical communications system can be used for ranging, the measurement of the time for a signal to travel between two communicating terminals. Optical frequency signals provide higher accuracy than radiometric measurements because they are not affected by charged particles in the signal path. To implement ranging into an optical communications system, JPL must develop appropriate modulation ranging, decoding of the ranging signal on reception, and precise timing of transmission and arrival of the ranging codes.



The deep space positioning system (DPS) instrument employs optical beacons, similar to GPS signals, to determine a spacecraft's position anywhere in the solar system. Pulsars and X-ray sources can also provide advanced navigation approaches. Ultra-stable deep-space-based timing systems enable one-way tracking measurements that simplify navigation by allowing many users to obtain tracking measurements simultaneously.



Scientists are proving the concept of using pulsars as a precise tool for deep space navigation. Known pulsars can be used like galactic light houses, enabling triangulation of a spacecraft's position by tracking the regular bursts of pulsars X-rays signals.

INSTRUMENTS AND SENSORS

EXAMINING OTHER WORLDS

SEE, SMELL, TOUCH, AND HEAR WITH REMOTE SYSTEMS

INTRODUCTION

Instruments and sensors gather information about local surroundings and distant phenomena.

All mission goals rely on instruments and sensors, and progressively more ambitious goals require more advanced instruments and sensors. Characterizing exoplanets requires greater sensitivity and efficiency. Searching for life on other planets requires more affordable and more precise approaches. Advancements in instruments and sensors enable new insights for every mission, from analyzing Earth's systems to studying the origins of the universe.

ROLE IN SCIENTIFIC DISCOVERY

Advancements in instruments and sensors enable new measurements, more precise measurements, higher resolution images, and surface exploration and sampling. High-efficiency radar modules elucidate Earth's weather processes and improve the accuracy of hurricane and storm prediction. The dynamic cycles that control Earth's climate and the anthropogenic effects that lead to changes are better understood. Highly sensitive detector arrays and spectrometers characterize the atmospheric composition of exoplanets. Biochemical sensors search for faint and microscopic signatures of life on planetary surfaces. Hazards and resources on other bodies are identified in preparation for human exploration.

BENEFIT TO JPL MISSIONS

As the lead NASA center for planetary exploration, JPL benefits significantly from advancements in science instruments and spacecraft sensors. Instruments and sensors with higher sensitivity, greater robustness, and reduced overall mass and power consumption enable more complex science missions and planetary missions. Intelligent sensors that build on the advancements in autonomy and artificial intelligence will expand the capabilities of scientific discovery. Astrophysics missions benefit from high angular and spectral resolution detection of signals across all spectral bands. Planetary missions accommodate the high cost of planetary landings with lighter and less expensive radar systems and in situ detectors. Planetary missions also benefit from the detection of surface hazards and resources, informing plans for future human space exploration. Increasing the sensitivity and raising the operating temperature of sensor technology grow our understanding of Earth's complex systems and provide new tools for understanding our planet.

Opposite: NASA's Europa Clipper will carry nine major instruments to study Jupiter's enigmatic moon.

CHALLENGES

Instrumentation that can capture weak signals over great distances presents a design challenge. Future astronomy and cosmology missions need ever-larger apertures to collect weak signals over great distances. However, as diameters exceed 4 meters, monolithic optics become too large to be feasible. In addition, to detect longer wavelengths, instruments must operate at colder temperatures, to prevent the instrument's own thermal emission from overwhelming the signals. At far-infrared wavelengths, for example, instruments must operate at a temperature of about 4˚K (-269˚C).

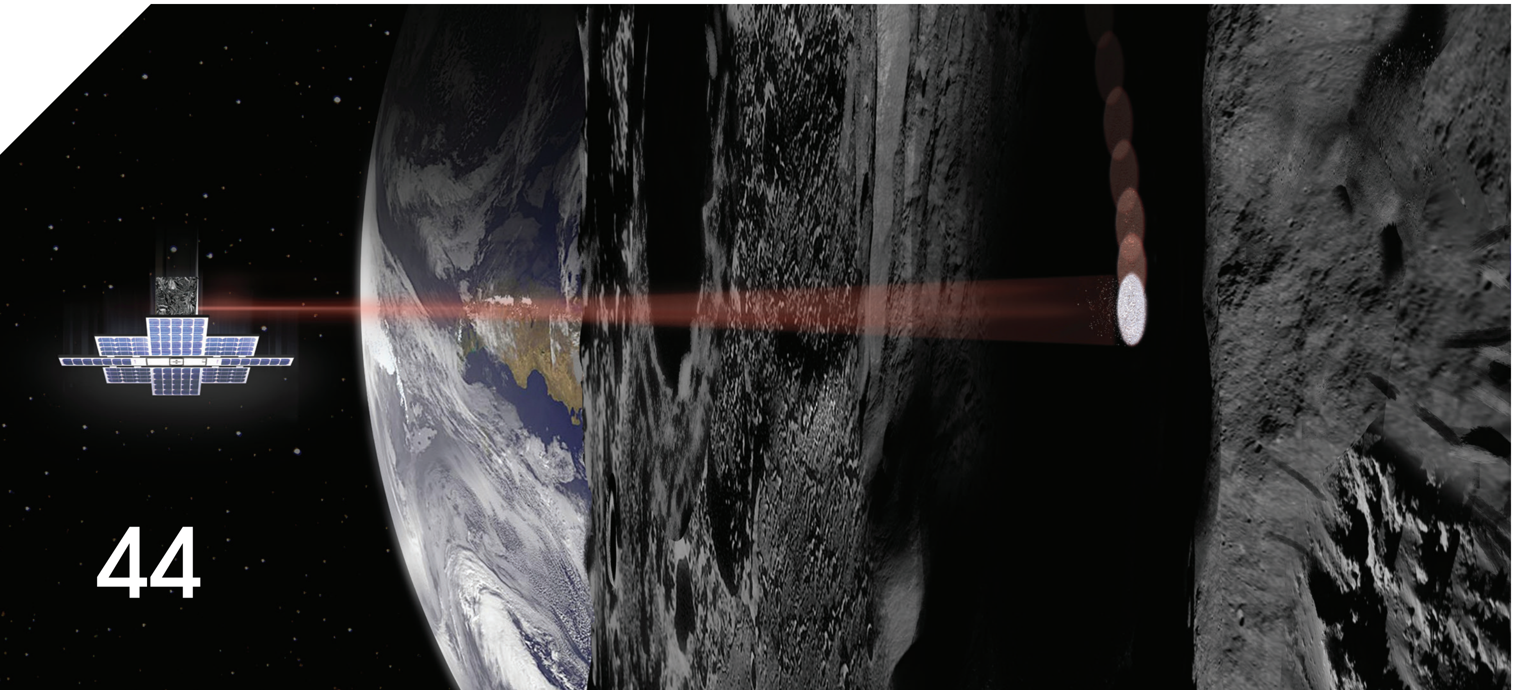
Planetary missions rely on sensing technology for landing, exploring, and sampling, but technology size and weight is a significant constraint. Radar systems are necessary for planetary landing, but the size of current radar systems overwhelms the cost of already expensive planetary landings. The high cost of planetary landings also necessitates significant reductions in the size and weight of in situ sensors.

SOLUTIONS

To address these challenges, JPL must advance instruments and sensors in four areas: direct detectors and optics, coherent detectors and arrays, active sensor systems, and in situ and life detection sensors. The chapters on miniaturized systems and advanced manufacturing, design, and materials also describe technologies and processes that can help reduce the overall mass of instruments and sensors without compromising robustness and sensitivity.

Direct Detectors and Optics

Direct detectors and optics passively detect light in ultraviolet, visible, and infrared wavelengths, to enable both local and remote sensing. Advances in direct detectors and optics improve sensitivity and resolution, increase array size, and reduce overall mass and power consumption. Technologies to develop in this area include semiconductor-based detectors, spectrometers, superconductor-based detectors, and adaptive optics.

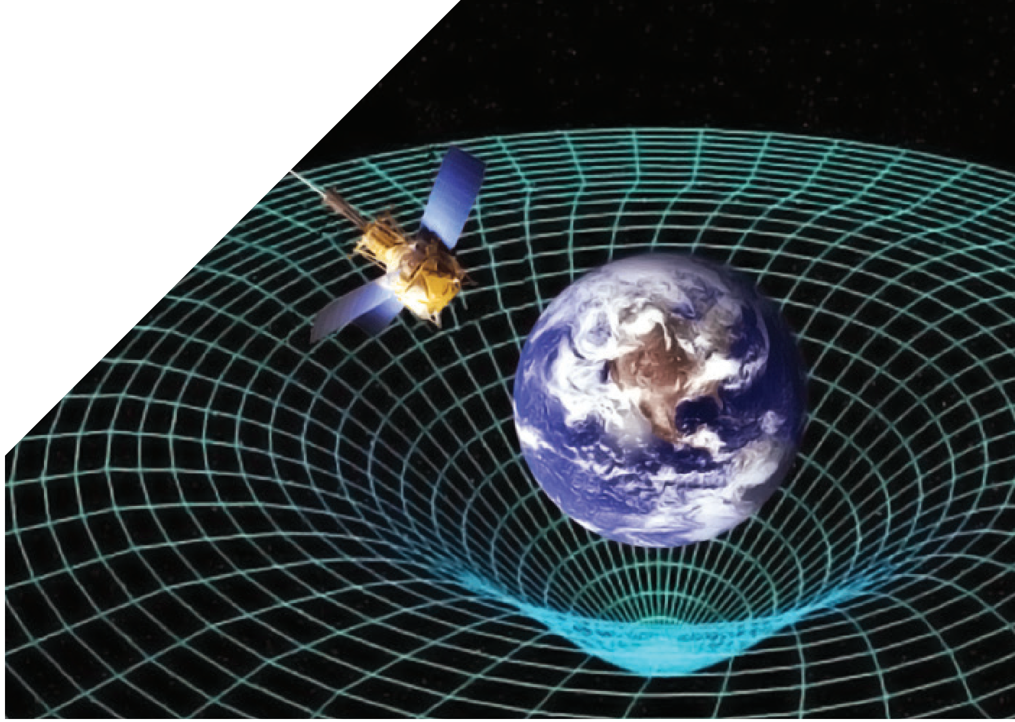


This artist's concept shows the Lunar Flashlight spacecraft, a 6U CubeSat designed to search for ice on the Moon's surface using infrared lasers. The spacecraft will use its lasers to shine light into shaded polar regions, while an onboard reflectometer will measure surface reflection and composition.

Semiconductor-based detectors can operate at higher temperatures while reducing mass and power consumption requirements. Semiconductor-based focal plane arrays (FPAs) optimize optical response and electronic signal collection and extend the range of high-performance arrays. Advancements in semiconductor-based FPAs can use fabrication and integration approaches to add more functionality and reduce overall mass. For example, fabricating flat sub-wavelength optical coatings replaces bulk refraction with interference effects to guide and focus incoming light and reduces overall mass by integrating at the pixel level. Other areas include targeted cooling of critical elements to reduce cooling power requirements and in-pixel digital readout electronics for faster response time.

Superconductor-based detectors enable higher sensitivity in instruments and sensors. For example, thin-film superconducting sensors enable astrophysics measurements in far infrared wavelengths. Advancements in this area include innovative readout technology to enable larger arrays, higher-operating-temperature superconducting sensors to enable passively cooled instruments for outer planet missions, and energy-resolving pixels to enable spectroscopy and imaging in a single array.

Adaptive optics enable the larger apertures that science missions need in order to collect weak signals over great distances. Advancements in this area include computer-optimized asymmetric free-form designs, beam-path control through self-interfering wavefronts using sub-wavelength patterning, and multifunctional optical elements. JPL can also pursue emerging quantum physics-based technologies to achieve precision impossible on current instruments and sensors. Finally, advancements in low-temperature metrology systems, beam sources, and actuators can reduce the costs associated with developing and operating actively controlled and segmented optics for large apertures.



Light wave–based interferometric measurement, imaging, and sensing capabilities can be greatly enhanced by novel measurement techniques that take into account the quantum nature of electromagnetic radiation.

Coherent Detectors and Arrays

Coherent detectors and arrays passively detect light in wavelengths longer than infrared, from radio to submillimeter waves. To detect weak signals at the millimeter and submillimeter length, JPL must develop new integrated receiver architectures and receiver arrays.

New integrated receiver architectures extend current single-pixel detection to arrays. One example architecture involves low-profile antennas using metal or dielectric metamaterials. This architecture uses sub-wavelength structures to guide and focus the radiation through resonant interactions instead of through bulk properties. Such an architecture can achieve efficient, low-profile antennas for millimeter- and submillimeter-wave instruments, with applications for radiofrequency communications as well.

Receiver arrays can detect weak signals at sufficiently low temperatures. To develop compact receiver arrays, JPL needs efficient frequency multipliers that can reach high local oscillator (LO) frequencies, efficient LO power distribution circuitry, and low-profile and highly efficient antenna arrays. For example, multipliers using superconducting non-linear elements can be orders of magnitude more efficient and significantly smaller than existing technology. Another area to develop further is electronically scanned and interferometric arrays, which can extend rapid imaging at the submillimeter level.

Active Sensor Systems

Active sensor systems control their own source of illumination for coherent or direct detection of something that cannot be passively sensed, such as structures below a planetary surface. The radar instruments that enable active sensing must become smaller and more affordable to accommodate smaller spacecraft and more complex planetary missions. Areas to develop further include low-mass, high-efficiency transmit/receive (T/R) modules, solid-state power amplifiers (SSPAs), digital electronics, and unique lasers.

Because some radar systems and arrays require many T/R modules, increasing the efficiency and lowering the mass of each T/R module improves the overall system. For example, single-chip monolithic microwave integrated circuit (MMIC) T/R modules are smaller, lighter, and potentially less expensive to manufacture in large numbers; MMIC T/R modules can enable phased-array antennas, which require large numbers of T/R modules. In addition to MMIC T/R modules, another area for development involves inkjet printing of electronics, to produce ultra-thin radiating patches with integrated T/R electronics.

SSPAs can provide a single high-power source, mitigating the need for an array of transmitters. SSPAs offer savings in mass and power consumption, but JPL must advance SSPA technology to become more efficient, particularly at higher frequencies.

Integrating digital electronics in RF components can simplify and enhance transmission. For example, digital-to-analog conversion can enable digital generation and supply of transmit signals to the SSPA or T/R modules. In addition, onboard radar image processing using high-density field-programmable gate arrays (FPGA) and application-specific integrated circuits (ASIC) can overcome communication-rate delays.

A variety of laser technologies unique to JPL missions can enhance scientific measurements and observations in space and on planetary surfaces. Unique sensors to develop include higher power, more efficient, tunable IR-to-UV lasers for chemical and mineralogical analysis; laser combs for spectroscopy and astrophysical measurements; solid-state lasers to generate beams for segmented or distributed optics metrology and for gravitational wave detection; pico- and femto-second pulse lasers for high-peak-intensity in situ spectroscopy without localized sample heating or damage; and high-power disk lasers for interplanetary communications and lidar instruments.

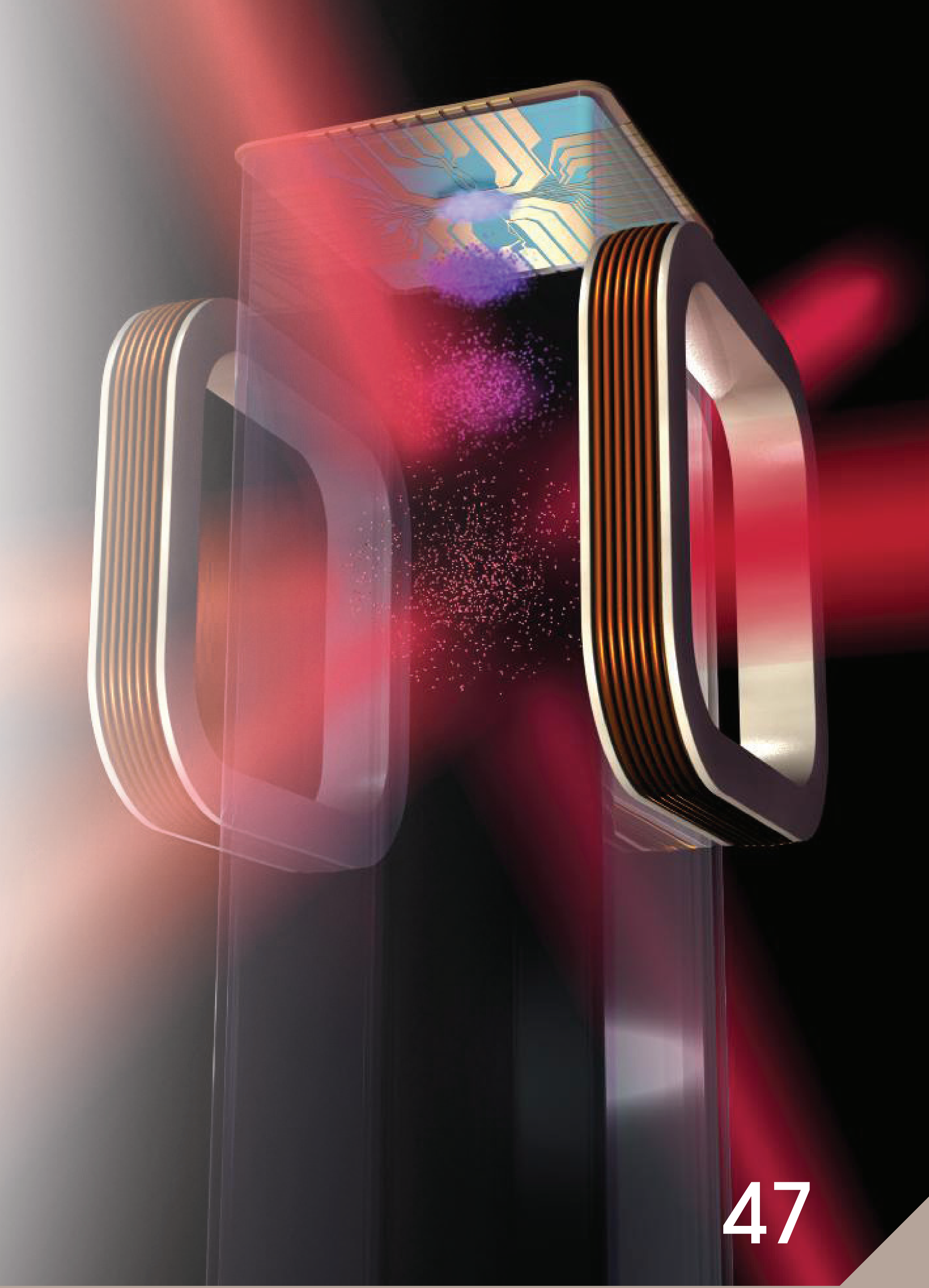
In Situ and Life Detection Sensors

Rather than detect light, in situ and life detection sensors focus on signatures such as seismic motion, electron scattering, and biochemical reactivity. In situ sensors also detect the presence of fields, such as electric, magnetic, and gravitational fields. New developments must enable in situ sensors to search for life and prepare for human exploration, including developments in organic analysis instrumentation, miniaturized microscopy, and miniature atomic quantum sensors.

Organic analysis instrumentation characterizes low-concentration organic materials. To reveal the range of biochemical signatures produced by life, these instruments must include precision analysis of molecular type, abundance, and chirality. One area to develop uses capillary electrophoresis to concentrate molecules of interest for detection with miniaturized biochemical sensors. Compact time-domain spectrometry is another technology to develop. Using excitation in the submillimeter range, where biological tissue tends to be transparent, this type of spectrometry enables the use of high-power probes without the risk of tissue damage.

Miniaturized microscopy can detect the presence of microstructure and motion associated with life. These microscopes must provide sub-micron spatial resolution with high sensitivity to cell-like particles. Two approaches can help JPL achieve this goal. The first approach involves digital holography applied to microscopy to produce digitally auto-focused, ultra-high-resolution 3D images and videos revealing cell-like particles and their motion. The second approach involves light-field imaging applied to fluorescent microscopy to detect and identify proteins, cell walls, and nucleic acids.

Miniature atomic quantum sensors use atom-wave interferometry to trap and manipulate cold atoms. The intrinsic atomic properties and quantum interference measurements provide new high-precision measurement capabilities for space position, navigation, and timing; seismometry and gravity science; and direct detection of dark matter, dark energy, and gravitational waves.



Better understanding of cold atoms and quantum gas will one day help JPL build advanced gravitational sensors to unravel the mysteries of dark matter and dark energy. Here, an artist renders a magneto-optical trap and atom chip that is furthering this research aboard the International Space Station.

ROBOTICS AND MOBILITY SYSTEMS

GOING WHERE WE CAN'T

MACHINES TO REACH PLACES HUMANS DARE NOT GO

INTRODUCTION

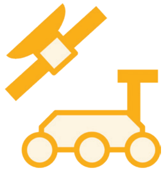
Robotics and mobility systems enable a spacecraft to physically engage with a space environment and traverse on the surface of large planets and small bodies.

All JPL missions use robotics, and increasingly complex missions require increasingly advanced robotic systems. Advancements in robotics and mobility systems increase the range and capabilities of JPL missions to planetary surfaces—exploring new environments, returning samples to Earth, and preparing for human exploration. Science missions in space also benefit, with teams of robots assembling large structures and enabling greater coverage for observations and measurements.

ROLE IN SCIENTIFIC DISCOVERY

Robotics systems perform in situ exploration to increase knowledge about the systems, origins, and habitability of planetary bodies. On ocean worlds, such as Europa and Enceladus, robotic explorers will rappel down crevasses, penetrate icy crusts, and swim below the surface. Aerial robots float through Venus's thick atmosphere, dive to its scorching surface to reach a target, and rise again to cool. Hybrid mobility systems fly through Titan's atmosphere, venture into its caves, and swim through its methane lakes. Other robotic systems bounce and slide around the crests and valleys of low-gravity bodies, exploring their surfaces. Another system collects samples on the surface of Mars and transfers the samples to a rocket for return to Earth, while maintaining cleanliness for planetary protection. These explorations reveal insights about the formation and conditions of planetary bodies, the potential for past or current life, or possibilities for future human exploration.

In space, advanced robotics enable greater coverage for astrophysics, astronomy, and Earth science. Robotic systems work as autonomous teams or beside astronauts to construct or repair large spacecraft. Apertures too large for launch are assembled in space to collect the most distant signals, providing new insights into the origins of universe. Robotic systems also increase coverage, access, and flexibility for Earth science investigations.



BENEFIT TO JPL MISSIONS

Advanced robotics and mobility systems enable new planetary missions with greater science return. New mobility systems can traverse areas that were previously inaccessible, for example, rappelling down cliffs to elucidate the history of layered deposits. In situ exploration of ocean worlds becomes possible for the first time ever. Sample return missions become more feasible and more affordable.

Opposite: Automaton Rover for Extreme Environments (AREE) is a clockwork rover inspired by mechanical computers. A JPL team is studying how this kind of rover could explore extreme environments, like the surface of Venus.

Teams of advanced robotic systems reduce the cost and risk of developing and maintaining large space structures. Launching disparate elements for in-space assembly reduces mission costs and enables the use of massive apertures for higher resolution imaging and detection. Teams of autonomous robots can optimize tasks among them and reconfigure to account for team member failures.

CHALLENGES

Increasingly complex science missions demand robust and autonomous robotics and mobility systems. Future planetary science missions involve accessing, exploring, and sampling extreme environments. For example, missions to Europa, Titan, or Enceladus might require a system to land on and traverse an extremely cold surface and penetrate an icy crust to reach a liquid ocean, without prior knowledge of the environment or human intervention. These and other missions require robotics and mobility systems that can mitigate unpredictable physical and chemical properties, variable physical mediums (gas, solid, liquid), diverse atmospheres, extreme hot and cold temperatures, high radiation, and energy-impoverished environments. In addition, missions that involve sampling require unique capabilities in a robotics system: to prepare, capture, analyze, and potentially preserve and return to Earth, gaseous, liquid, or solid samples of varying compositions.

SOLUTIONS

To address these challenges, JPL must advance robotic perception and localization, mobility systems, manipulation and sampling systems, and multi-robot teams and in-space assembly. These areas are intertwined with solutions

Exploring distant planetary bodies with dynamic environments will require innovative mobility solutions. Here the Exobiology Extant Life Surveyor (EELS) uses a first of its kind rotating propulsion unit that acts as wheels, grippers, and propeller to explore a plume and follow it to its source.

discussed in Autonomous Systems; Artificial Intelligence and Machine Learning; Miniaturized Systems; Advanced Manufacturing, Design, and Materials; Distributed Systems; and Robotics and Mobility Systems.

Robotic Perception and Localization

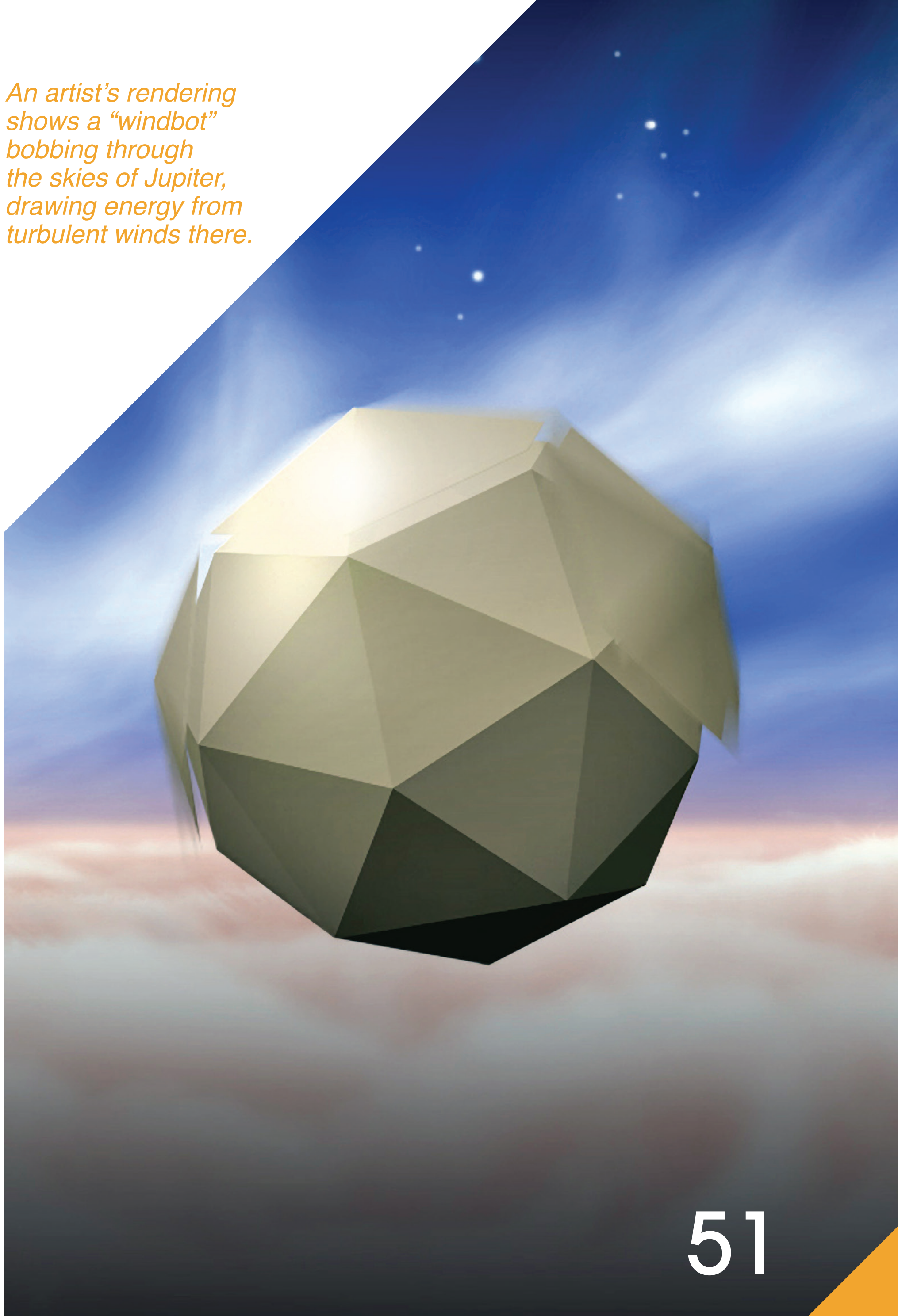
Robotic perception and localization enable object recognition and position determination, broader mapping for mobility, and self-positioning within the environment. To better adapt this technology for use in space, JPL must develop electro-optical (EO) stereo camera systems and sensing and localization algorithms beyond the current state of the art.

Passive EO stereo camera systems enable 3D sensing for planetary robotics. These low-power and low-mass systems have a wide field-of-regard, high angular resolution, and few moving parts. Developing EO stereo for space robotics includes adapting new modalities, such as active sensing for environments with little ambient light; incorporating smart cameras to off-load processing; and developing panoramic viewing systems and algorithms to combine data from multiple sensing systems.

Sensing and localization algorithms enable capabilities such as deep learning, data fusion, automated camera calibration, and pose estimation. JPL must develop algorithms that can run efficiently on space-qualified electronics. JPL also needs algorithms for unique perception and sensing challenges, such as detecting rocks and other landscape features from the types of imagery likely to be available, including in environments with harsh glare and shadows. Another potential enhancement is the capability to derive location and pose from past observations or outdated views.

Mobility Systems

Mobility solutions take multiple forms depending on the specifics of the destination and mission goals. Emerging



An artist's rendering shows a "windbot" bobbing through the skies of Jupiter, drawing energy from turbulent winds there.

mobility systems, such as dynamic biped and quadruped systems, must be adapted for use in space. In addition to leveraging state-of-the-art commercial technology, JPL must continue to develop creative mobility approaches for a range of anticipated environments.

JPL needs low-energy, agile, robust explorers that can acquire measurements at multiple sites rapidly and reliably. Focus areas for development include extreme-terrain mobility for access to compelling sites, above-surface mobility for broader and faster coverage, below-surface mobility through natural and fabricated cavities and holes, small-body and microgravity mobility, and control of tethered systems for extreme terrain access. Exploring bodies with atmospheres (Titan, Venus, Mars) requires new configurations of aerostat (lighter than air) and aerodyne (heavier than air) robotic mobility systems.

Manipulation and Sampling Systems

Manipulation systems enable missions to grab, hold, and manipulate a wide variety of objects securely. Sample acquisition physically interacts with a previously uncharacterized environment to extract and handle a sample without compromising its structural or compositional characteristics. To extend the possible uses for these systems, JPL needs advancements in drilling, autonomous sampling systems, and robotic manipulators.

Drilling technology is necessary for acquiring subsurface samples. JPL must develop specialized drilling technologies capable of subsurface access over a wide range of depths, compressive strengths, and temperatures.

Autonomous sampling systems identify desired sampling locations and react to anomalous conditions, enabling continued sampling operations without human intervention. JPL must develop autonomous sample assessment and transfer to in situ instruments. Autonomous sampling also requires new deterministic mechanisms for sample transfer and sensing to validate transfer success.

Robotic manipulators for in situ planetary exploration missions must operate with extremely high reliability and robustness in extreme, dynamic environments. Technology development in explosive ordinance disposal, underwater systems, and terrestrial sampling applications can guide JPL efforts to improve the mobility and dexterity of robotic manipulators for space missions.

Multi-Robot Teams and In-Space Assembly

Multi-robot teams and in-space assembly enable in situ robotic assembly of disparate elements into a larger system.

In-space construction and servicing manipulates, stabilizes, and attaches multiple construction elements simultaneously. JPL must develop cooperative manipulation of orbiting systems with complex dynamics, planning and communication, and approaches for system- and agent-level human interaction that provide varying levels of autonomy.

For in situ construction and assembly, teams of surface and flying robots can cooperate to move and assemble large structures and coordinate to handle unwieldy parts and sub-assemblies. A cooperative manipulation capability that can operate in a gravitational field and with greater autonomy will be needed.

Teams of robots working together to complete complex missions can accomplish more science with specialized capabilities. This is an artist's impression of a team of robots exploring Mars.

STRATEGIC TRACEABILITY

NATIONAL STRATEGIC INPUT

NATIONAL ACADEMIES

DECADAL SURVEYS

NASA relies on the science community to identify and prioritize leading-edge scientific questions and the observations required to answer them. One principal means by which NASA's Science Mission Directorate engages the science community in this task is through the National Research Council (NRC). The NRC conducts studies that provide a science community consensus on key questions posed by NASA and other U.S. government agencies.

NATIONAL SPACE COUNCIL

NATIONAL SPACE POLICY

In 2017, President Trump reconstituted the National Space Council. The NSpC bridges the gap between the Executive Office, NASA, and commercial space activities. It establishes broad goals and objectives for the U.S. space program.

NASA GOALS AND OBJECTIVES

NASA STRATEGIC PLAN

The plan emphasizes space exploration while affirming NASA's commitment to the advancement of science and aeronautics.

DISCOVER

Expand human knowledge through new scientific discoveries

UNDERSTAND the Sun, Earth, Solar System, and Universe

EXPLORE

Extend continuous human presence deeper into space and to the moon for sustainable long-term exploration and utilization

CONDUCT human exploration in deep space, including to the surface of the Moon

DEVELOP

Address national challenges and catalyze economic growth

DEVELOP and **TRANSFER** revolutionary space technologies to enable exploration capabilities for NASA and the Nation

INSPIRE and **ENGAGE** the public in aeronautics, space, and science

ENABLE

Optimize capabilities

ENGAGE in partnership strategies

SUSTAIN infrastructure capabilities and operations

JPL STRATEGIC IMPLEMENTATION PLAN

STRATEGIC THEMES, PRIORITIES, AND GOALS

QUESTS

PURSUE a diverse and bold set of science missions

THRUSTS

CREATE the laboratory of the future

FUTURE CAPABILITIES

ACCELERATE technology infusion

JPL STRATEGIC TECHNOLOGIES

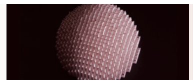
DISRUPTIVE

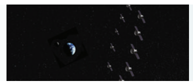

AUTONOMOUS SYSTEMS


ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING


DATA SCIENCE

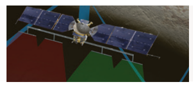

MINIATURIZED SYSTEMS


ADVANCED MANUFACTURING, DESIGN, AND MATERIALS


DISTRIBUTED SYSTEMS

LEGACY


COMMUNICATION AND NAVIGATION


INSTRUMENTS AND SENSORS


ROBOTICS AND MOBILITY SYSTEMS

STRATEGIC TECHNOLOGIES ENABLE SIP CAPABILITIES

STRATEGIC TECHNOLOGIES

FUTURE CAPABILITIES

	Autonomous Systems	AI and Machine Learning	Data Science	Miniaturized Systems	Advanced Manufacturing, Design, and Materials	Distributed Systems	Communications and Navigation	Instruments and Sensors	Robotics and Mobility Systems
Life detection, astrobiology		●		●				●	●
Autonomous systems and AI	●	●	●	●			●	●	●
Smallsats	●	●		●	●		●	●	●
Additive manufacturing		●			●				
In-space robotic assembly	●	●		●		●	●	●	●
Constellations, swarm systems	●	●	●	●		●	●	●	●
In-situ science	●	●	●	●	●	●	●	●	●
High-performance space computing		●	●	●	●				
Advanced detectors				●	●			●	
Quantum sensing and communications		●	●	●	●		●	●	
Augmented and virtual reality		●	●	●					
Big data, data analytics		●	●				●		

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ACRONYMS

3D	Three Dimensional
6DOF	Six-Degrees-Of-Freedom
AI	Artificial Intelligence
AMDM	Advanced Manufacturing, Design, and Materials
AREE	Automaton Rover for Extreme Environments
ASIC	Application-Specific Integrated Circuit
CAD	Computer Aided Design
CCA	Complex Concentrated Alloy
COTS	Commercial-Off-The-Shelf
DPS	Deep Space Positioning System
DTN	Disruption Tolerant Network
EELS	Exobiology Extant Life Surveyor
EO	Earth Observation
FDIR	Fault Detection, Identification, and Recovery
FPA	Focal Plane Array
FPGA	Field-Programmable Gate Array
GaN	Gallium Nitride
IR	Infrared
JPL	Jet Propulsion Laboratory
K	Kelvin
LO	Local Oscillator
MAV	Micro-Air Vehicle
MEMS	Microelectromechanical Systems
ML	Machine Learning
MMIC	Monolithic Microwave Integrated Circuit
MPEA	Multi-Principle Element Alloy
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NDS	Networked Distributed System
OCT	Office of the Chief Technologist
PAT	Pointing, Acquisition, and Tracking
PUFFER	Pop-Up Flat Folding Explorer Robot
RF	Radio Frequency
RHBD	Radiation-Hard-By-Design
SIP	Strategic Implementation Plan
SNSPD	Superconducting Nanowire Single Photon-Counting Detectors
SSPA	Solid-State Power Amplifier
SunRISE	Sun Radio Interferometer Space Experiment
T/R	Transmit/Receive
UQ	Uncertainty Quantification
UV	Ultraviolet
V&V	Verification and Validation

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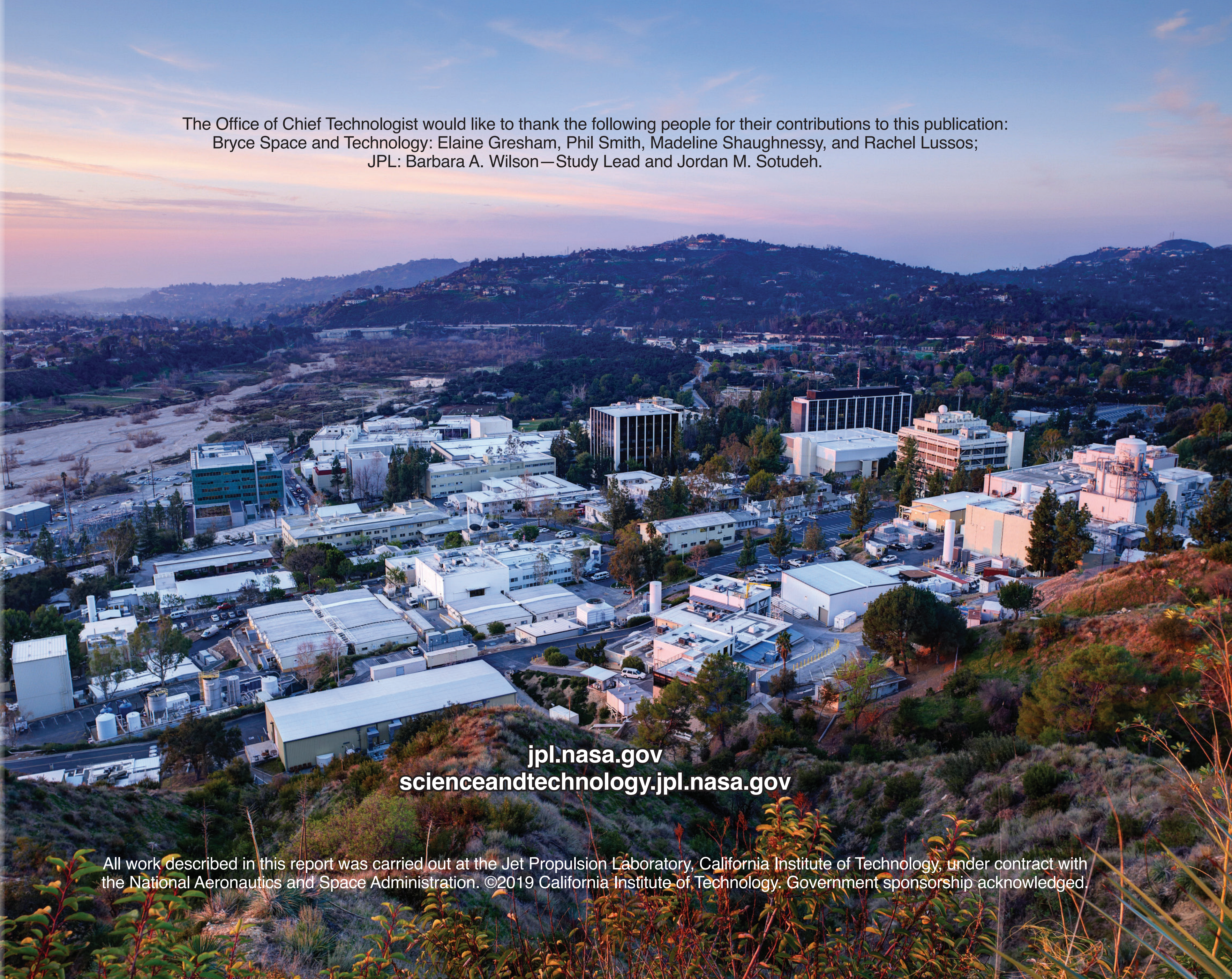

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