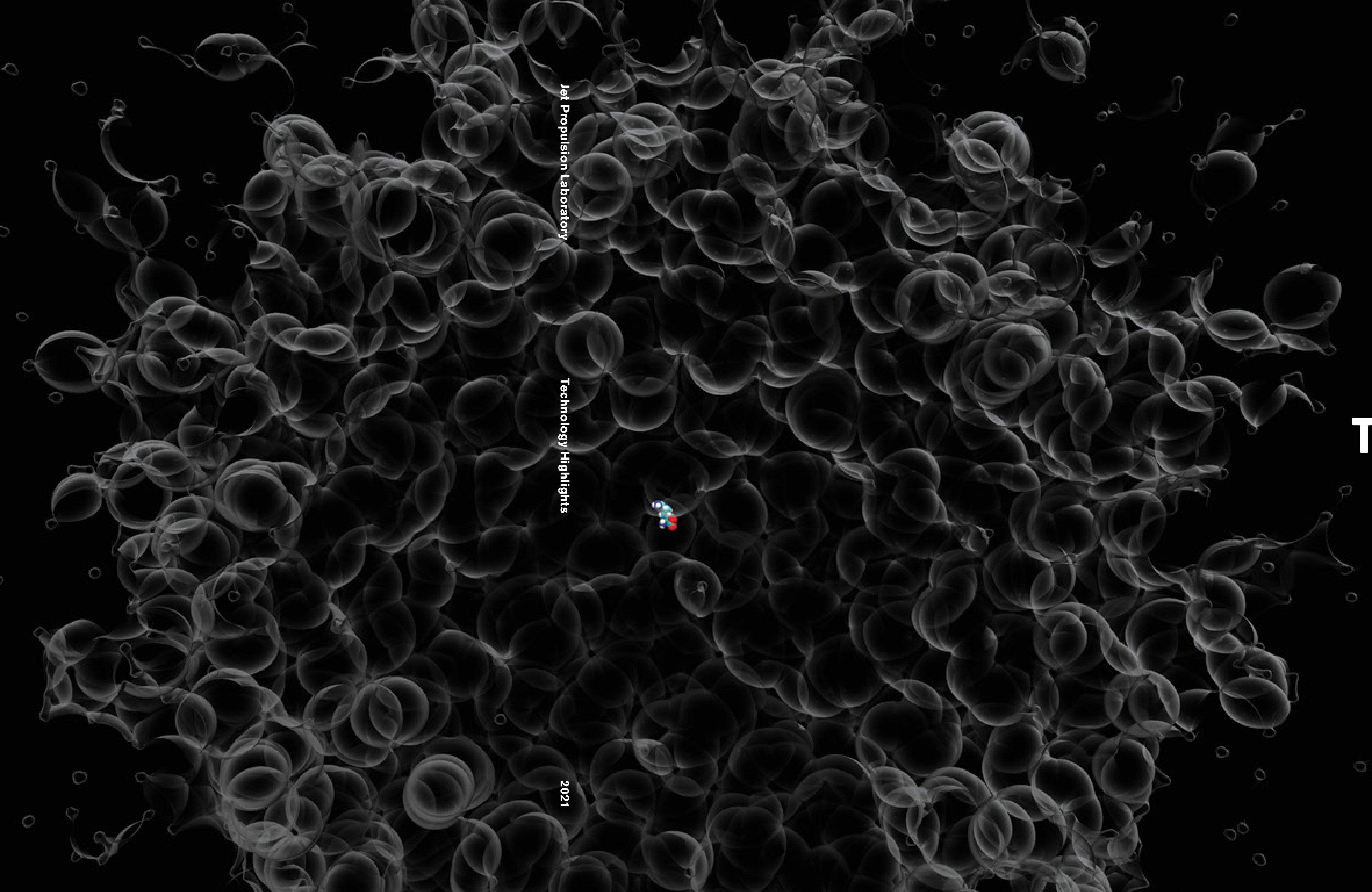
National Aeronautics and Space Administration

2021 TECHNOLOGY HIGHLIGHTS

Jet Propulsion Laboratory



Jet Propulsion Laboratory
Technology Highlights
2021

National Aeronautics and Space Administration

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California Institute of Technology
Pasadena, California

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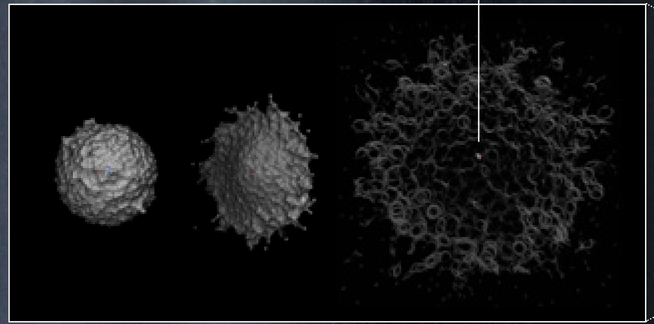
OFFICE OF THE DIRECTOR

JPL is a place for exploration and discovery, where our achievements reflect the amazing possibilities that arise when you bring together the best minds in science, technology and engineering. The exploration of our Earth, Solar System and the broader universe challenges individuals and teams to meet and overcome unforeseen obstacles in the pursuit of knowledge. All through this long pandemic, our community has kept alive its innovative spirit for the benefit of NASA, our nation, and the world.

The successful landing of Perseverance and the flight of the Ingenuity helicopter on Mars was the perfect example of the drive and determination of our community. Perseverance has already captured samples for an eventual return to Earth and Ingenuity offers an entirely new Mars mobility system that makes it possible to look for unique signatures in areas that are simply impossible to reach with our current rovers.

The pages in this book offer a glimpse toward the future technology capabilities that are conceived and being developed by our innovative people and collaborators. I welcome you to examine our innovative technologies and to join us in advancing the future of robotic space exploration.

LARRY JAMES
JPL Interim Director



On the cover is the computer simulation of arginine amino acid encased in a 6.4 nm ice grain survives a simulated hard impact at 5 km/s. This provides quantifiable insight into future instrument design and mission parameters for hypervelocity sampling of biosignatures from ocean world atmospheres and plumes.

SIMULATING SIGNS OF LIFE IN AN ICY VEIL

NEW RESEARCH REFINES TECHNIQUES FOR SAMPLE COLLECTION AT ICY MOONS LIKE ENCELADUS

The detection of life on icy moons such as Enceladus would be one of the most profound scientific accomplishments of the 21st century. One way to accomplish this is to collect ice grains—which may contain biomolecules—from the watery plumes that are emitted from the moon's surface, but to succeed we must better understand what happens when these tiny grains are collected by the spacecraft.

JPL and Caltech have partnered to determine what happens during high-speed collisions, as occur when the grains or bare molecules impact a rigid surface. Developing unique methods and supercomputer modeling tools to accurately predict and describe the physical and chemical events that occur during hypervelocity impacts is critical. In as little as a femtosecond (one quadrillionth of a second), the ice is vaporized and any remaining molecules are ionized. This ionization allows instruments like mass spectrometers to detect and determine the identities of the resulting molecules.

This is a delicate process, however; if the impact velocity is too high, the molecules of interest can fragment; if the velocity is too low, the molecules may not ionize. The impact needs to fall in a sweet spot for biomolecule detection, orbital speeds which range from 1.8 miles per second (3 kilometers per second) to 3.7 mps (6 kps)—at higher speeds the ice covering the target molecules fails and the molecules fragment, making analysis difficult. If future missions to icy bodies like Enceladus target speeds in this range for plume collection, these new techniques may provide evidence of life without the complexities of landing on the moon's surface.

OFFICE OF THE CHIEF TECHNOLOGIST

The history of JPL is one of technological vision and innovation, and we continue to build on that legacy. Our community is driven to expand knowledge through innovation and technological advances leading to major scientific discoveries. Technologies conceived and developed by JPL and our partners improve our understanding of the changing planet, offer deeper insight into the mysteries of our solar system, provide information that helps trace the origin and fate of the universe, and extend our reach toward finding the building blocks of life within our solar system and beyond.

These technologies—including autonomous systems, quantum sensing, additive manufacturing, smart materials, advanced sensors, deployable systems, novel power systems, AI and machine learning, to name just a few—have been strategically identified to support JPL's role as one of the world's preeminent centers for robotic exploration of the universe, while accelerating leadership in critical and emerging technologies aligned with important challenges of national interest.

In this 2021 edition of JPL's Technology Highlights, I invite you to join me in recognizing the diversity of people, ideas, creativity, and inventions that are a hallmark of the JPL technology community. The exploration of our universe is humanity's greatest adventure, in which we are honored to participate.

FRED HADAEGH
JPL Chief Technologist

AND WHAT GREATER MIGHT DO WE POSSESS AS HUMAN BEINGS THAN OUR CAPACITY TO QUESTION AND TO LEARN?

—ANN DRUYAN

JPL's 2021 Technology Highlights is a brief summary of some of our most impressive technology developments over the past year. This work impacts our research objectives from the Earth to the Moon and Mars, throughout our solar system, and to the furthest reaches of the observable universe. Our objective is to enable space exploration for NASA in collaboration with our partners. Some missions are in early development, while others are ready for launch or in operation, but all have the same objective—knowledge and discovery of the unknown. And while we proudly share our technology accomplishments represented herein, ultimately it is the wide range of skills and talents of our people—less visible in this year's publication due to COVID impacts—that we celebrate here.

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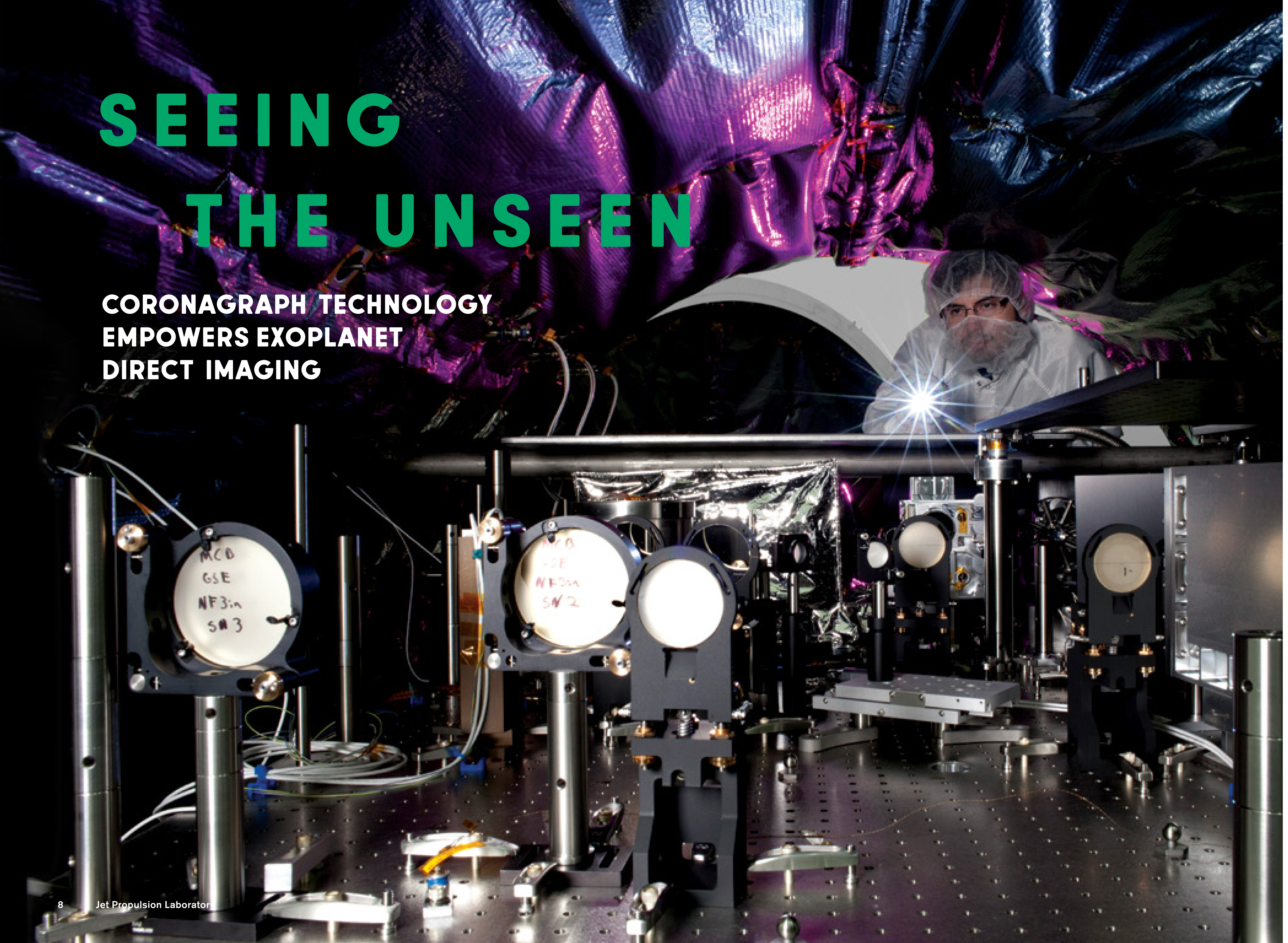
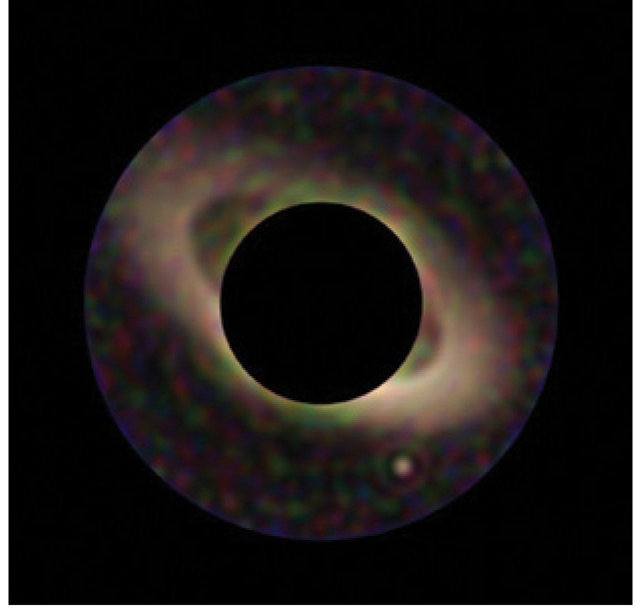


SEEING THE UNSEEN

CORONAGRAPH TECHNOLOGY EMPOWERS EXOPLANET DIRECT IMAGING



Simulation of expected image with CGI on Roman of a planet (at about 5 o'clock) with a zodiacal dust cloud.

Earth-like planets have been found in the habitable zones of stars throughout our galaxy. Finding water vapor, methane, or carbon dioxide in the atmospheres of these worlds could indicate the presence of life. This can be accomplished by imaging these exoplanets directly, which requires precise starlight suppression technology. An Earth-sized planet orbiting a Sun-like star is about 10 billion times dimmer than and is normally lost in a star's glare. A device called a coronagraph can be used to suppress this glare, using a set of masks behind the telescope's optics to block the host star's light, allowing faint nearby planets to be imaged.

Coronagraphs have been used on Earth-based telescopes to image distant exoplanets, but the Earth's atmosphere limits these measurements to planets that are much brighter and larger than the Earth. Coronagraphs have also been flown on the Hubble Space Telescope but have lacked adaptive optics to correct optical errors, and were further limited by structural instability of the telescope due to heating and cooling of the spacecraft. These are serious limitations for such critical, distant observations.

JPL is building a Coronagraph Instrument (CGI) for the Roman Space Telescope (previously known as WFIRST), scheduled for launch in 2026, that will be the first coronagraph to fly in space with adaptive optics. It will be able to detect and characterize planets more than 100 million times dimmer than their host stars by using deformable mirrors to correct noise from optical imperfections.

The National Academies' 2020 Decadal Survey in Astronomy and Astrophysics recommended that NASA develop technology for a 20-foot (six-meter) space telescope capable of directly-imaging at least 25 Earth-like exoplanets in the 2040s. Coronagraphs will likely be critical to such missions, and may lead to the discovery of life on another planet, a transformative achievement that would change humanity's view of itself and our place in the universe.

ADAPTIVE OPTICS AND ADVANCES IN CORONAGRAPH TECHNOLOGY MAKE DIRECT IMAGING OF EXOPLANETS POSSIBLE.

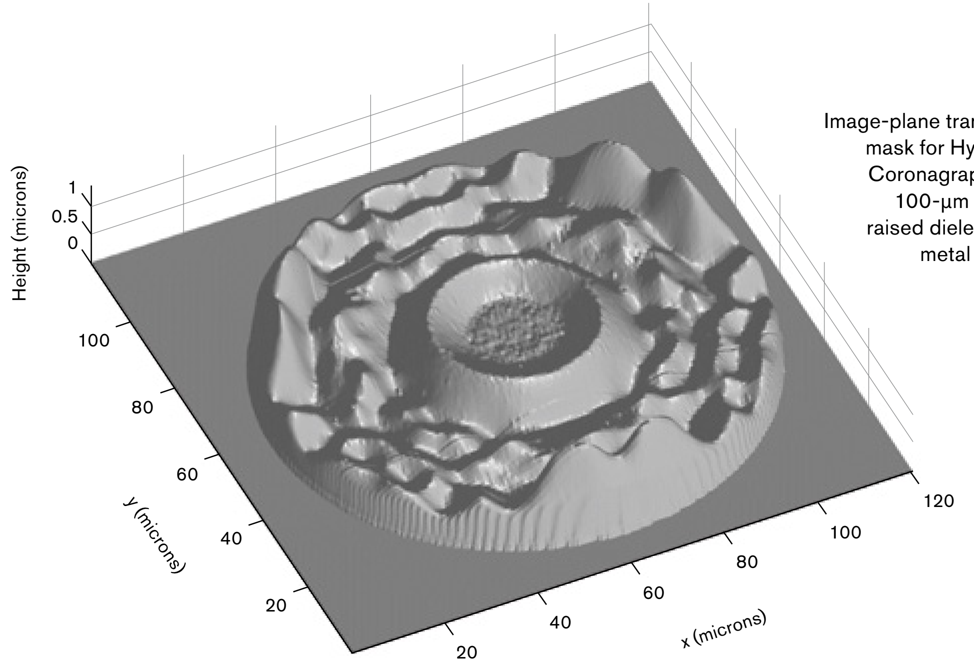
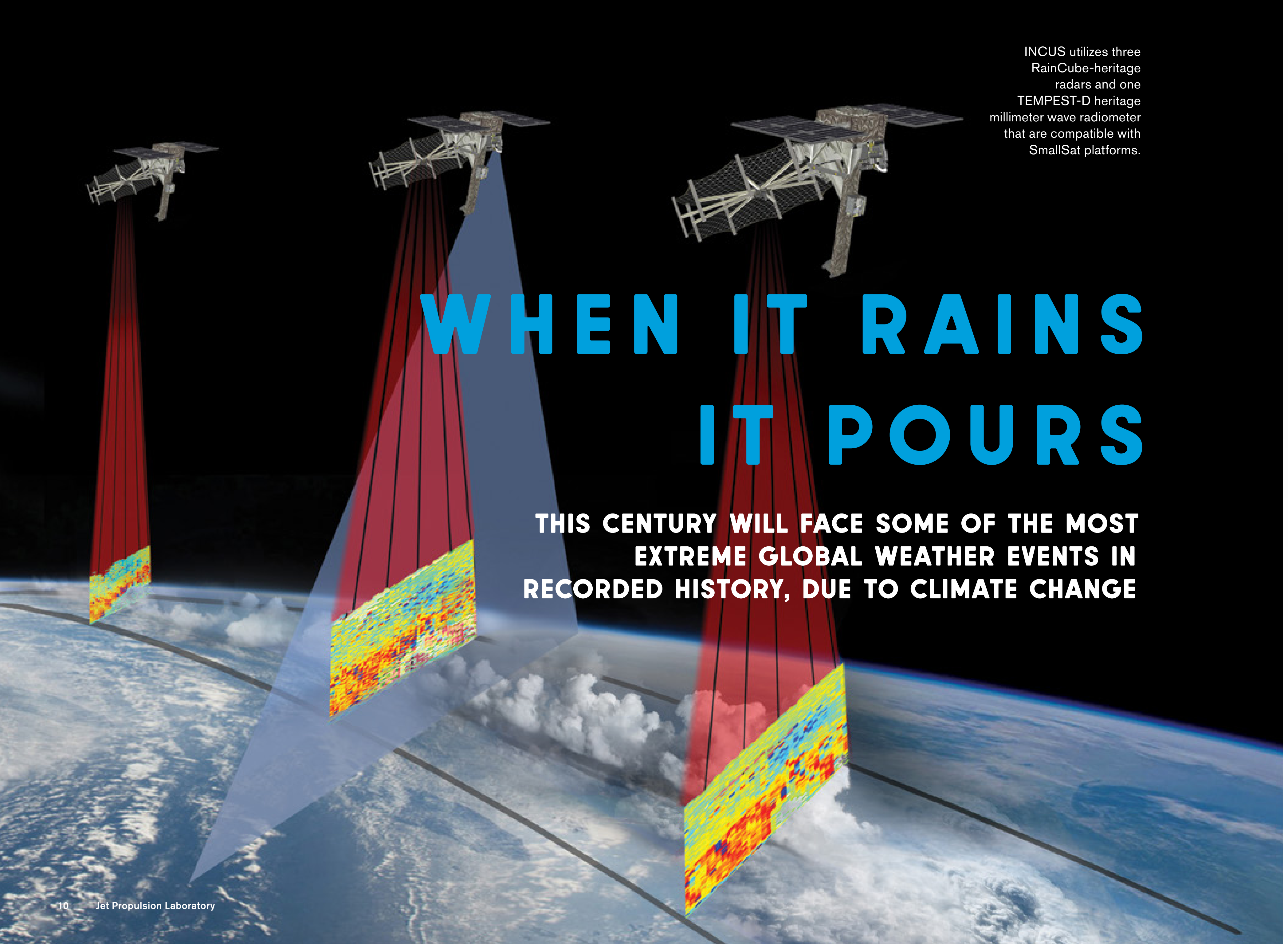


Image-plane transmitting mask for Hybrid Lyot Coronagraph (HLC), 100-µm diameter, raised dielectric and metal on glass.



INCUS utilizes three RainCube-heritage radars and one TEMPEST-D heritage millimeter wave radiometer that are compatible with SmallSat platforms.

WHEN IT RAINS IT POURS

THIS CENTURY WILL FACE SOME OF THE MOST EXTREME GLOBAL WEATHER EVENTS IN RECORDED HISTORY, DUE TO CLIMATE CHANGE

Life on Earth is bound to weather and convective storms, from the fresh water they supply to the extreme weather they produce. These storms transport water and air, a property typically referred to as convective mass flux (CMF), between Earth's surface and the upper atmosphere (the troposphere). The transport of moisture in tropical convective storms plays a critical role in Earth's weather and climate system through its influence on storm intensity, rates of precipitation, upper tropospheric moistening, and the large-scale circulation of moisture, and appears to be in flux due to our changing climate. Much of this activity is still poorly understood, especially with regard to extreme weather events that can impact large areas and vast numbers of people. Systematic measurements of convective mass flux would improve the representation of storm intensity, and help to constrain high cloud feedbacks in weather and climate models, potentially saving both life and property around the globe.

Recent advances in small satellite remote sensing instruments and related technologies will improve our understanding of these severe weather events. The Investigation into Convective Updrafts (INCUS), led by Colorado State University and managed by JPL, is a recently selected NASA Earth Ventures Mission. INCUS consists of three SmallSats that will orbit Earth in close formation armed with JPL-developed miniaturized radar and radiometer technologies. The overarching goal of INCUS is to understand why, when, and where tropical convective storms form, and why only some storms produce extreme weather. This understanding will lead to improved weather and climate forecasting models.

THE 21ST CENTURY WILL FACE SOME OF THE MOST EXTREME GLOBAL WEATHER EVENTS IN RECORDED HISTORY DUE TO CLIMATE CHANGE, AND INCUS WILL HELP US TO BETTER UNDERSTAND THEM.

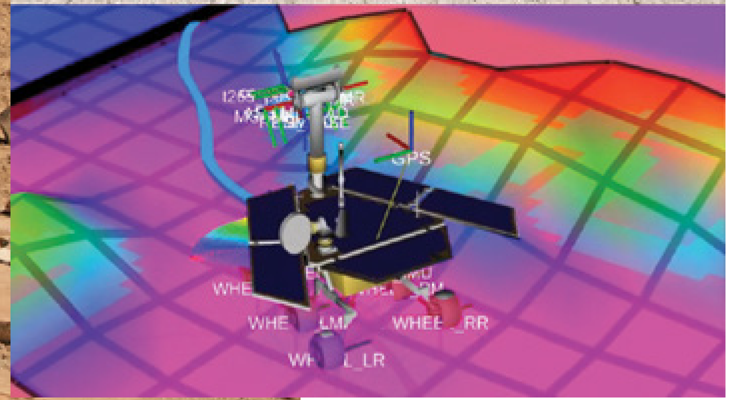
INCUS is expected to launch in 2027 and builds upon NASA's previous technology flight demonstration missions RainCube and TEMPEST-D that laid the groundwork for SmallSat constellation science in response to the Earth Science Decadal Survey. The result will be enhanced prediction of severe weather events—and mediation of their consequences—in some of the most densely populated regions of the world. The potential savings in property damage and life are incalculable.

Towering cumulonimbus thunderstorm clouds are seen in this photo taken Aug. 15, 2014, looking east toward the Atlantic Ocean from the Space Launch Complex 37 area at Cape Canaveral Air Force Station (now Cape Canaveral Space Force Station) in Florida. NASA has selected a new Earth science mission called Investigation of Convective Updrafts (INCUS) that will study the behavior of tropical storms and thunderstorms, including their impacts on weather and climate models.

Machine learning-based Analytics for Automated Rover Systems (MAARS) is demonstrated on the Athena rover test unit in the JPL Mars Yard.

TO BOLDLY ROVE

AI AND MACHINE LEARNING ENABLE AUTONOMOUS ROVING



During a semi-live rover demo, the Athena rover demonstrates on-board fully autonomous long-range driving, one of its novel autonomy capabilities.

Driving slowly across a Martian plain on a typically chilly afternoon, Perseverance cross-checks the path ahead with the maps in its digital brain. After pondering the discrepancies, the rover adjusts to the right, handily avoiding a large, sharp rock not visible from orbit.

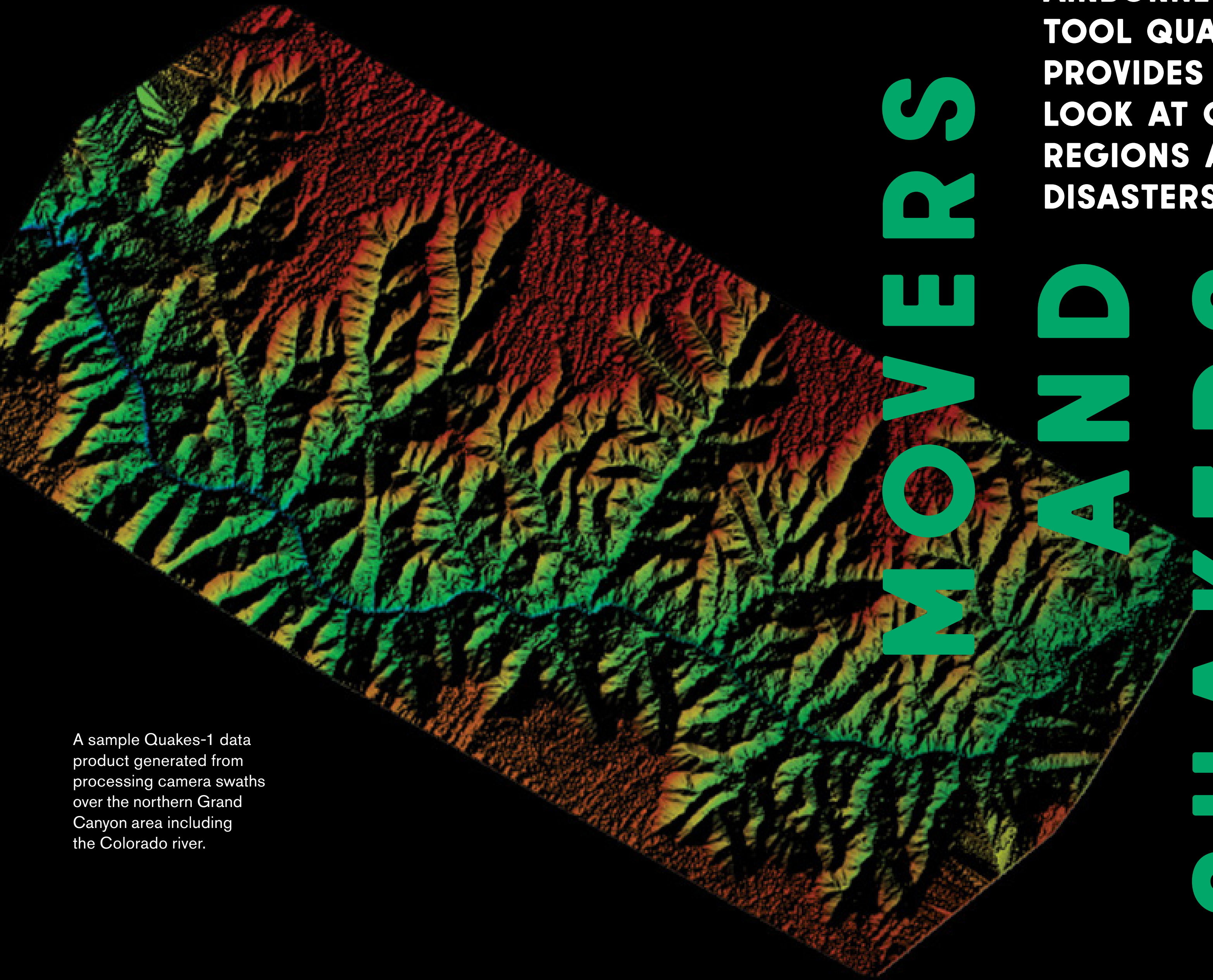
Artificial intelligence has just saved the day again.

Due to the extreme distance between Earth and Mars, averaging 140 million miles, radio commands can take as long as 24 minutes to reach machines exploring the Red Planet. It is simply not possible to "joystick" these systems from Earth. What if they could perform more rapidly and independently? Artificial intelligence and machine learning make all the difference—allowing the rover to think for itself.

A team of JPL engineers is developing the Machine Learning-based Analytics for Automated Rover Systems (MAARS) suite of machine-learning tools to enable this new era of planetary exploration, enabling the rover and its Earthbound team to work with more accuracy and efficiency than ever before. MAARS system components are named after Star Trek characters, and like those legendary heroes of the Enterprise bridge, each has a critical job to perform. The SULU software interprets real-time images from the rover's NAVCAMs as it drives, SPOC classifies terrain textures as well as features seen on the ground ahead. With this information, VEEGER develops a map of safe and energy efficient routes to traverse. RAND, while accounting for in-route battery recharging, calculates the best path forward. All the while, SCOTI analyzes SULU's imagery and prepares it in a database for UHURA to communicate back to scientists on Earth, enabling better mission planning than ever before.

> **COMBINING SEVERAL ADVANCES IN MACHINE LEARNING-BASED ANALYTICS ENABLES ROVERS THAT CAN DRIVE TWICE AS FAST AND AMASS MORE DISCOVERIES ALONG THE WAY.**

In 2020, using the Athena rover testbed on Earth, the MAARS system autonomously drove twice as fast as the Perseverance rover does on Mars. Where past rovers might miss important details because they were not specifically commanded to look for them, MAARS was able to intelligently reason about features and relationships seen in the terrain. In the near future, smart systems like MAARS should allow us to develop safe and efficient robotic explorers that will act increasingly not just as tools, but as valuable partners in planetary exploration.



A sample Quakes-1 data product generated from processing camera swaths over the northern Grand Canyon area including the Colorado river.

MOVERS AND SHAKERS

AIRBORNE FAST-SURVEY TOOL QUAKES-1 PROVIDES A DEEPER LOOK AT CRITICAL REGIONS AND NATURAL DISASTERS

The QUAKES-I instrument structure.

Understanding the intricacies of wide regions of earthly terrain is more difficult that you might think. We have, of course, been conducting ground-level surveying since ancient times—the Egyptians needed to understand local terrain to build the pyramids, for example, but this is only effective across relatively small areas. Since the age of flight, airborne surveying has allowed the general characterization of wide regions, but the data gathered is limited in detail and scope. The ability to gather highly granular data across wide swathes of territory has been highly coveted across many industries.

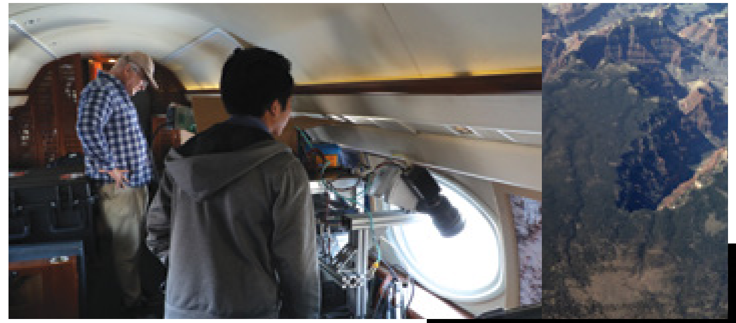
The QUAKES-I instrument (Quantifying Uncertainty and Kinematics of Earth Systems Imager) is a structure-from-motion sensor developed by JPL to produce high resolution 3D terrain data products for the scientific community. The instrument consists of two sensor suites mounted on a Gulfstream jet aircraft. The first sensor is downward looking providing dense, high resolution terrain reconstruction from two groups of four cameras that each cover 7.5 miles by two miles (12 kilometers by 3 kilometers), accumulating a terabyte of information each hour. The second sensor looks to the side, providing images for context and lower-resolution structure, from a four-camera array across visible and infrared frequencies in conjunction with a synthetic aperture radar instrument.

A NEW AIRBORNE, HIGH-RESOLUTION TERRAIN SURVEY TOOL AIDS IN EARTHQUAKE FORECASTS AND NATURAL DISASTER RECOVERY.

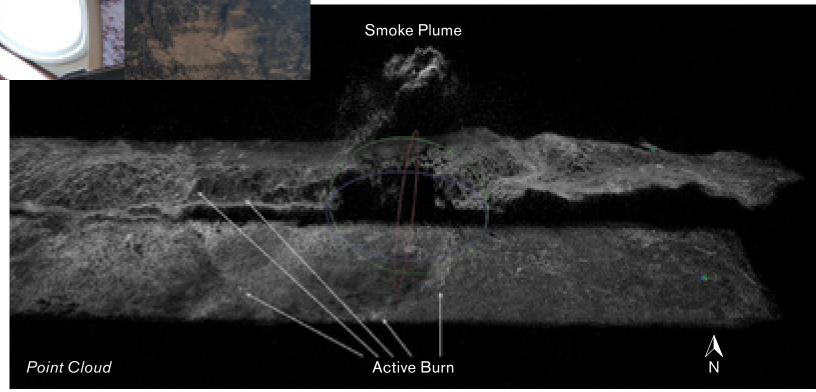
When combined with the main high-resolution data, detailed image maps provide insights into plate tectonic motion and structure, damage assessment of disaster zones from earthquakes, mudslides, and other natural occurrences, and general support for disaster relief QUAKES-I can also look through smoke and haze to aid firefighters working on large wildfires.

The visible imagery collected by the instrument combines the images with maps to provide a geo-rectified 3D terrain map and data point cloud for use in change detection studies (to better understand plate tectonic motion) and other surface phenomena. Test flights over the Western U.S. examined the highest and lowest areas of California, coastal regions, earthquake faults, along with general topography from Arizona.

In states like California, where earthquakes represent an existential threat, a better understanding of faults and tectonic boundaries is critical. And when disaster strikes, be it an earthquake, mudslide, or wildfire, minutes count. A detailed survey of affected terrain that can be launched quickly can be of critical benefit to recovery efforts, and QUAKES-1 is that tool.



The Quakes-1 system includes 2 SWIR and 2 visible imagers that are coincident with the SAR sensor. From left to right, the system aimed out of a passenger window, a captured image, and its 3D reconstruction.

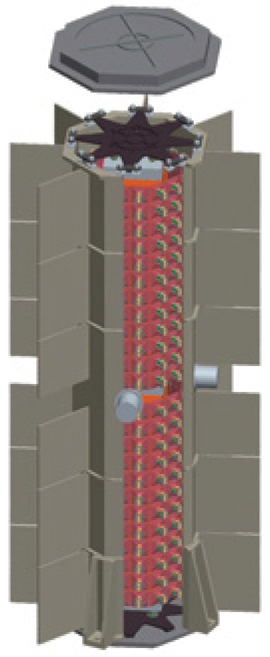


A fabricated thermoelectric (TE) module, based on new designs and customizable materials, that will help to extend the life of deep space missions.

THE HEAT IS ON

EXTENDING THE LIFE OF DEEP SPACE MISSIONS BY DECADES

Spacecraft have been using radioisotope power systems since the 1960s. NASA's twin Voyager spacecraft, launched in 1977, continue to operate using their Radioisotope Thermoelectric Generators (RTGs) some 45 years after launch, as they speed through interstellar space. Yet even nuclear power supplies have their limits—while radioactive half-life is a fixed part of the equation, the materials and thermocouples surrounding the hot fuel plug are the biggest limiting factor. These thermocouples convert the long-lasting heat source into electricity, the lifeblood of any deep space probe. Over decades, the materials that convert the heat from the radioactive element degrade, with power output suffering accordingly. Over time, the power output of the Voyager RTGs has declined by roughly 30 percent, while the heat output of the plutonium that supplies the heat in them has declined by less than 20 percent.

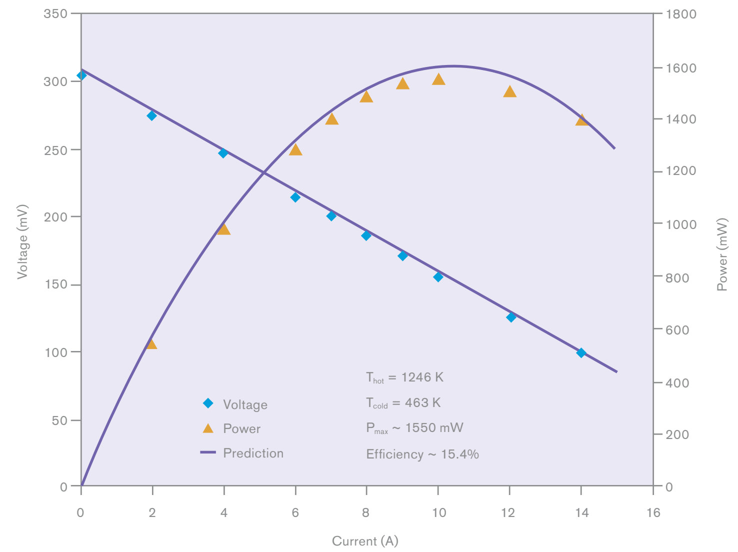


A conceptual design of an advanced RTG power source incorporating new, high-performance thermoelectric materials.

NEW DESIGNS AND MATERIALS SIGNIFICANTLY BOOST RADIOACTIVE POWER SOURCE PERFORMANCE.

The long-serving standard for RTGs has been silicon-germanium or lead-telluride conversion systems. These have proven to be rugged and reliable, but their overall efficiency is only about six percent when converting heat into power.

JPL technologists have designed and tested variants of these proven systems that improve conversion efficiency to about 15 percent, more than doubling their output. These new designs use highly-customizable materials called Zintl-phase mixtures—salt-like intermetallic compounds—that are crafted to exacting specifications to provide excellent conversion efficiency, yet are sufficiently robust to withstand the harsh conditions of launch and extended spaceflight. These changes will add decades to the life of RTG power sources and, for a given power level, require less radioisotope mass or provide more power for a given mass.



This graph shows the 15 percent thermal-to-electric conversion efficiency in an RTG enabled with JPL's new Zintl phase thermoelectric designs. Current designs have about six percent efficiency. The increase in efficiency can result in longer, more effective deep space missions.

The use of radioactive materials such as plutonium, americium, and others in RTGs was a boon to planetary exploration; a breakthrough technology for the 20th century. New materials for the conversion of these long-lasting heat sources into usable energy—at ever-higher efficiencies and with longer duty lives—will be a breakthrough for the 21st.

A team of CADRE mini-rovers cooperatively explore the JPL Mini Moon Yard as a precursor to a future flight demonstration.

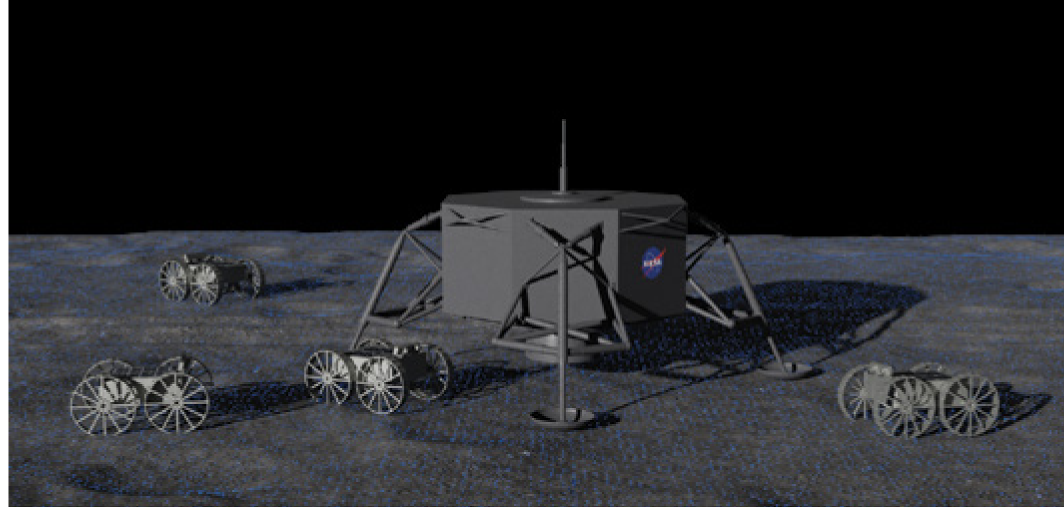
THE LITTLE ROBOTS THAT COULD

COOPERATIVE, AUTONOMOUS ROBOTS OPEN NEW SCIENTIFIC TARGETS

Size and mass matter greatly when exploring the solar system, especially when delivering robots to planetary surfaces. A new breed of small, autonomous scouting rovers is under development that may redefine how we explore lunar and planetary terrain. These machines are smaller (about the size of a shoebox), faster, more nimble, and less expensive than the larger "parent" rovers and landers they are designed to augment.

The CADRE (Cooperative Autonomous Distributed Robotic Explorer) project is helping to pioneer these new robots. Imagine that a lander has descended near a lunar cave or lava tube. What's inside? Is the entrance treacherous? CADRE mini-rovers, dispatched from the lander, will allow exploring such important lunar features which offer great potential rewards—with greatly reduced risk. Caves and lava tubes may hold water ice, a vital resource, and may provide suitable sites for a crewed lunar base.

A prototype CADRE mini-rover is tested at JPL. Inset is the digital elevation map created by the tiny robot.



An artist's impression of CADRE rovers deployed from a lander on the Moon's surface.

Other potential applications include emplacing networks of ground penetrating radar stations or radio telescopes spread across a lunar plain, creating regional subterranean structure maps, or performing high-resolution astrophysical investigations.

CADRE robots will have sufficient intelligence and autonomy to explore independently while operating as a smart multiple-robot network. They will be instructed to explore specific targets, returning data in occasional batches, with instructions for future operations relayed from the parent lander, reducing dependency on communication with Earth—an important issue when dealing with future, distant solar system missions.

CADRE technology is slated for lunar tests under NASA's Commercial Lunar Payload Services (CLPS) Initiative, where a suite of mini-rovers will work in tandem with each other and the parent lander, pooling resources holistically while still allowing individual units to undertake risky explorations. This investigative sharing allows for the creation of wide-ranging three-dimensional maps, a unique ability of CADRE robots.

EXPLORING RISKY TERRAIN ON THE MOON AND MARS WITH SMALL, AUTONOMOUS ROBOTS.

Eventually, fleets of small, self-aware mini-rovers may explore wide-ranging areas on the Moon, Mars, and the icy moons of the outer solar system, greatly expanding the capability of an individual lander or rover with less mission risk.

A simulation of how a 7.9-foot (2.4 meter) strip aperture telescope can provide Hubble-like resolution, where rotating the telescope gives access to all the directions of resolution.

APERTURE IS EVERYTHING

A DISRUPTIVE APPROACH TO LARGE APERTURE TELESCOPE DESIGN

It's tough to put a telescope into space. The United States has been launching telescopes since the late 1960s, but until now, the diameter of these orbiting instruments has been constrained by the size of a rocket's payload fairing or, in the past, the width of the shuttle's payload bay. As an example, the famed Hubble Space Telescope has an 8-foot (2.4 meter) primary mirror and was the largest telescope that could be launched using the space shuttle. The new James Webb Space Telescope has an effective aperture of 21 feet (6.5 meters) but to fit within its launch fairing, its primary mirror is comprised of a complex arrangement of 18 folding mirror segments that will deploy after launch. To create vastly larger telescopes, new and innovative approaches are needed.

A new technology under development at JPL employs a telescope design approach that only requires a narrow slice of the traditional primary mirror to achieve a full aperture. Called a Rotating Synthetic Aperture (RSA) telescope, this approach uses a reflective concave strip as its primary mirror.

The iris in this lens has been replaced with a strip-aperture pupil replicating the essential physics of RSA imaging.

Completing the Picture. The set of raw frames taken over a half rotation of the RSA telescope contains everything needed to reconstruct the full-resolution science product, rivaling the capabilities of much larger space telescopes, but using a much smaller package.

Science images are collected as the telescope rotates while maintaining line of sight to its astronomical target. After a half-rotation, the set of images is then digitally processed to reconstruct the scene. The results are spectacular, with the science product containing the same information as if it were acquired with a large circular telescope whose primary mirror diameter is the length of the RSA strip. This approach maximizes the telescope's effective diameter while using the least amount of hardware possible and may well lead to space telescopes with 100-meter apertures and beyond.

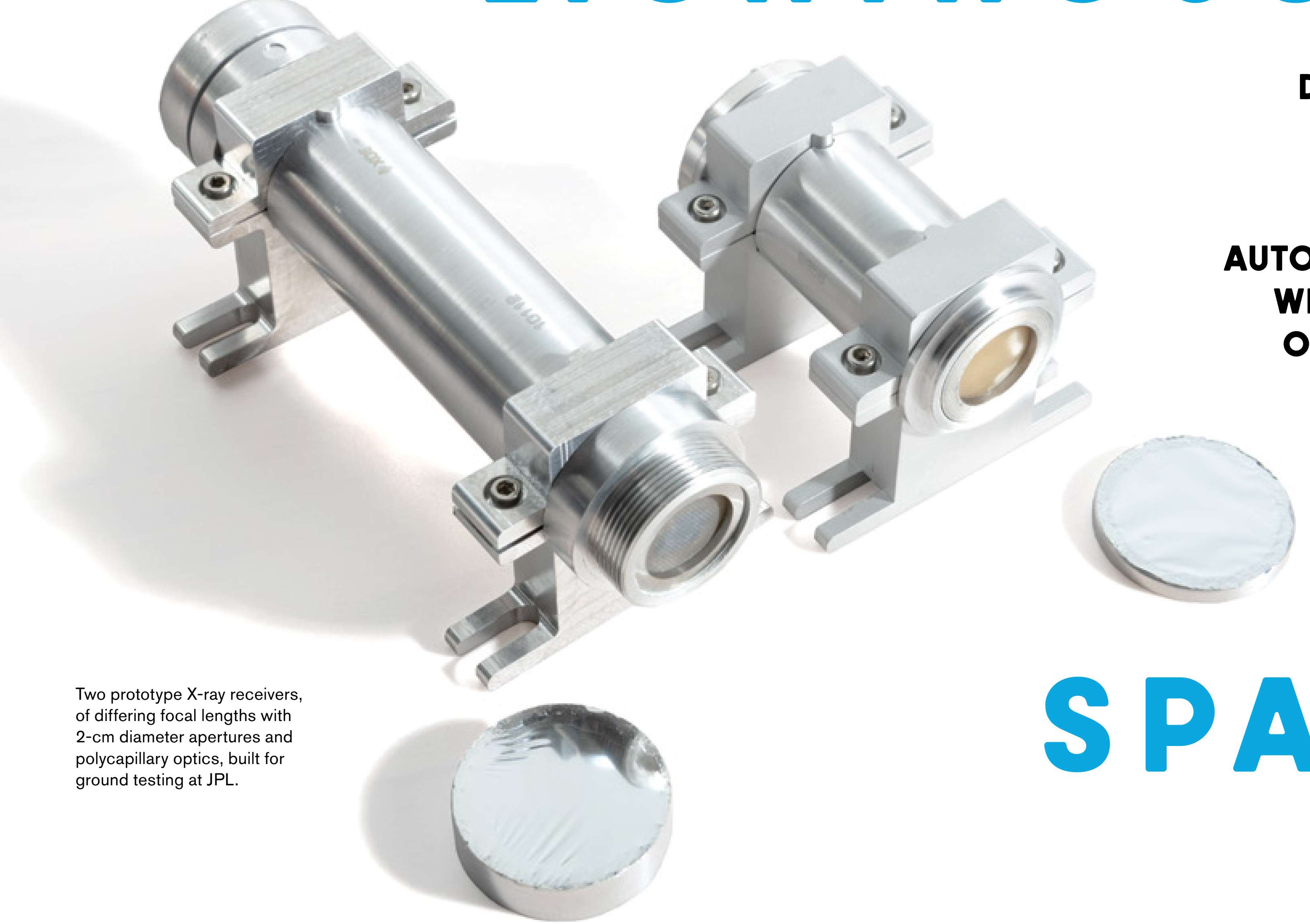
Using inexpensive off-the-shelf components, a demonstration version of the Rotating Synthetic Aperture camera has been tested, yielding very promising results. Further development, with larger scale systems, may open entirely new high-resolution observation approaches to astronomers, synthesizing far larger apertures than can be fit within a launch vehicle today.

A ROTATING SYNTHETIC APERTURE, WITH ADVANCED PROCESSING, MAY REVOLUTIONIZE FUTURE ASTRONOMICAL OBSERVATIONS.

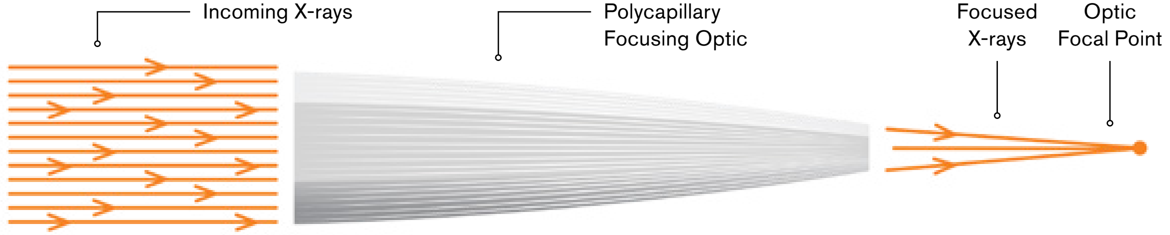
LIGHTHOUSES

DEEP SPACE MISSIONS MAY SOON NAVIGATE AUTONOMOUSLY WITH THE AID OF NATURE'S BEACONS—PULSARS

IN SPACE



Two prototype X-ray receivers, of differing focal lengths with 2-cm diameter apertures and polycapillary optics, built for ground testing at JPL.



Incoming X-rays are focused by a bundle of millions of small glass capillaries, shaped to redirect the X-rays' grazing incidence to a much smaller focal spot. In this way the effective field-of-view of an X-ray detector, positioned at the focal spot, can be significantly increased.

Navigating a probe through deep space is devilishly tricky. For one thing, signals from Earth take many hours to cross the void, and roundtrip communications double that. Onboard navigation and timing solutions are improving—including compact atomic clocks—but, like navigating a ship at sea, beacons at known locations are a godsend.

Using advanced optics technology developed for the Mars 2020 PIXL X-Ray fluorescence spectrometer, JPL engineers have developed an approach to utilize millisecond pulsars to significantly reduce the need for Earth-based spacecraft tracking. Millisecond pulsars are rapidly rotating neutron stars that emit precisely-timed pulses of X-rays. These precise energy bursts are predictable and reliable, with known small spin-down (or slowing) rates, that will remain stable over the life of even very long missions. Analyzing these signals allows for extremely precise determination of a spacecraft's location in space. Pulsar navigation has been successfully demonstrated, but the demonstration instrument was too large and power-hungry to be useful for practical spacecraft navigation.

USING TECHNOLOGY DEVELOPED FOR THE MARS PERSEVERANCE ROVER, PULSAR-TRACKING DEVICES MAY ENABLE ONBOARD, NEARLY AUTONOMOUS NAVIGATION IN DEEP SPACE.

A small prototype X-Ray pulse receiver, leveraging flight designs and spare parts from the PIXL instrument, has been tested using simulated pulsar signals. The 2-centimeter diameter polycapillary optic (a device designed to focus X-rays), composed of millions of small glass tubes, uses grazing incidence to focus X-rays onto a detector for reliable and sensitive tracking of pulsar signals. Since pulsars are quite distant and their signals very faint, future designs will increase the diameter of the prototype optics to 10 centimeters, creating a larger aperture to gather more photons and reduce position uncertainty. As larger apertures increase noise due to background X-ray radiation entering the system, a polycapillary collimator must be added in front of the optic to reduce the optical field of view to reject such noise.

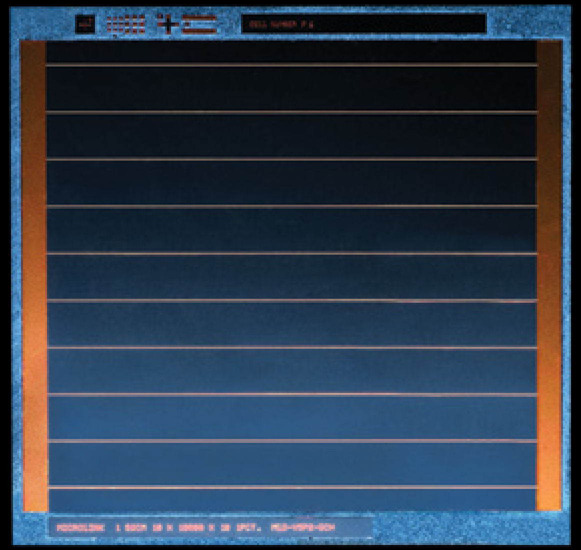
By cleverly employing nature's gifts—in this case, bright stars and predicable pulsar signals—future deep-space voyagers can maximize autonomy and science return without requiring huge investments in specialized research and development or Earth-based tracking systems.

Artist's impression of a deep space mission using X-ray pulsar navigation.

TAKING IT TO EXTREMES

EXTENDING VENUS SURFACE MISSION LIFETIMES FROM HOURS TO MONTHS

These gallium indium phosphene-gallium arsenide solar cells have been optimized to function on the surface of Venus and may be able to operate, with suitable protection, for seven weeks or more.



Closeup view of the improved solar cell design.

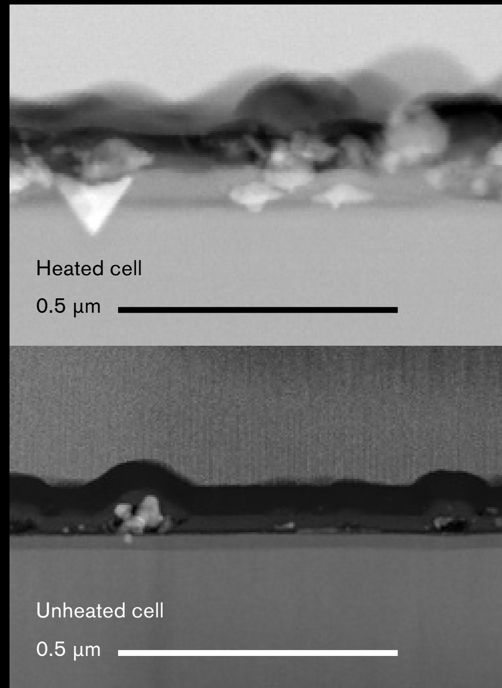
Venus has long suffered second-class status in the minds of many scientists, but this fascinating planet has much to offer. It may still be volcanic, it may have had plate tectonic activity, and it may have harbored life on the surface or possibly in the upper atmosphere today. Having not been visited by a dedicated mission since the 1990s, it is ripe for exploration—so much so that NASA recently selected two missions to visit Venus in the next few years.

NOVEL PHOTOVOLTAIC CELL TECHNOLOGY FOR LONG-TERM POWER GENERATION IN EXTREME ENVIRONMENTS.

While orbiters are quite effective for gross characterizations of the planet, ground truth exploration of its surface is something of a holy grail for planetary scientists. But its surface is quite inhospitable, with temperatures averaging 872 degrees Fahrenheit (467 Celsius) and atmospheric pressure estimated to be 100 times that of Earth. What's more, acid rain sweeps the surface. This is not a good environment for electronics, and in particular for power systems—previous landers have only lasted a couple of hours at most.

Technologists at JPL have developed a new solar power cell that is extremely resistant to high temperatures and harsh conditions. These advanced solar cells have been shown to be capable of surviving for weeks in Venusian conditions, and with improvements they may last for months. A specially crafted antireflective coating to protect against corrosion, material changes to slow degradation, design changes for stability at high temperatures, and encasement of sensitive parts all contribute to the new design. While Venus does not receive as much light on its surface as Earth does due to its cloudy atmosphere, solar power is still a very promising avenue of development for surface probes.

With new developments in overall lander technology, which even includes extremely robust rover designs, these improved power sources could be a game changer for the exploration of Earth's nearest planetary neighbor. There is much to be learned from Venus, possibly including how to mitigate climate change—the planet is home to the solar system's most profound runaway greenhouse effect. The 2020s may well be the decade of Venus and finding better, more survivable, ways to power landers is an enormous step forward.



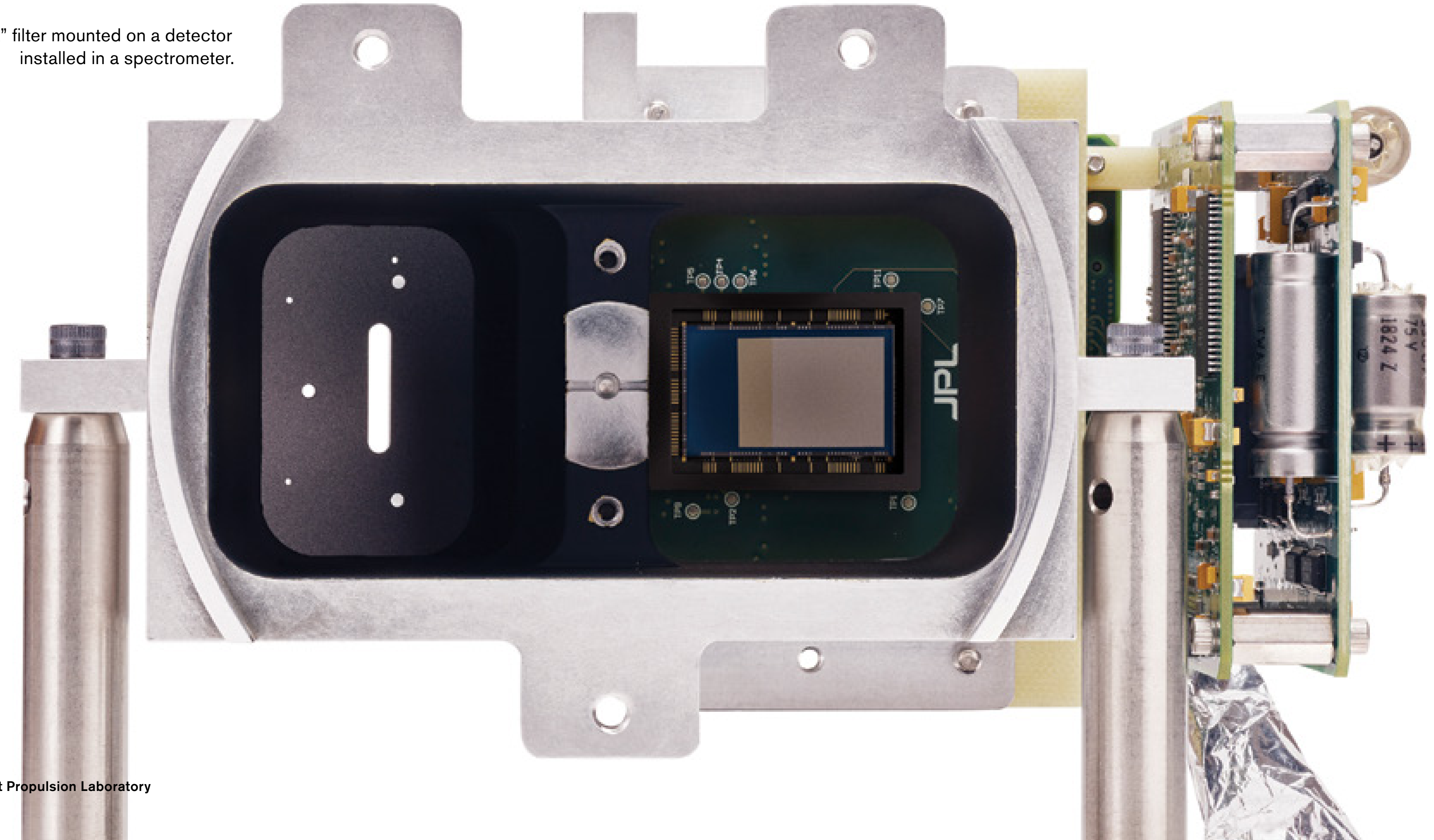
Top: Cross-sectional view of the solar cell, while heated, looking at the interface between the anti-reflective protective coating and the cell's surface. Silver melt droplets form, extending deep into the semiconductor layer.

Bottom: Cross-sectional view of the solar cell when unheated. While the melt droplets lead to some contamination across the cell's layers, which can lead to failure, it is less severe than in the heated solar cell than in the heated solar cell.

SENSE AND SENSITIVITY

DETECTORS OPTIMIZED FOR UV SPECTROSCOPY

“Block” filter mounted on a detector installed in a spectrometer.



Not all sensors are created equal. For instruments such as spectrometers working in the ultraviolet, there is often no “one size fits all” detector with the sensitivity to cover the entire desired operating range. To create a detector that has sensitivity optimized for the desired range, coatings can be applied selectively to different detector areas. The challenge is that traditional fabrication techniques used to pattern coatings and filters—like shadow-masking—are not compatible with the proven Atomic Layer Deposition (ALD) process being used in JPL’s Microdevices Laboratory.

For decades, detectors have been designed with uniform optical sensitivity across their entire focal planes; the wavelength response measured at one end of the device matches the wavelength response at the other. Uniform sensitivity limits detector performance, especially at ultraviolent wavelengths, because the anti-reflection or filter coatings typically applied target a central wavelength rather than the broad set of wavelengths of interest. Spectroscopy applications, then, can often benefit from a spatially-varying wavelength response, optimized according to the way the instrument disperses (spreads) wavelenths across the detector.

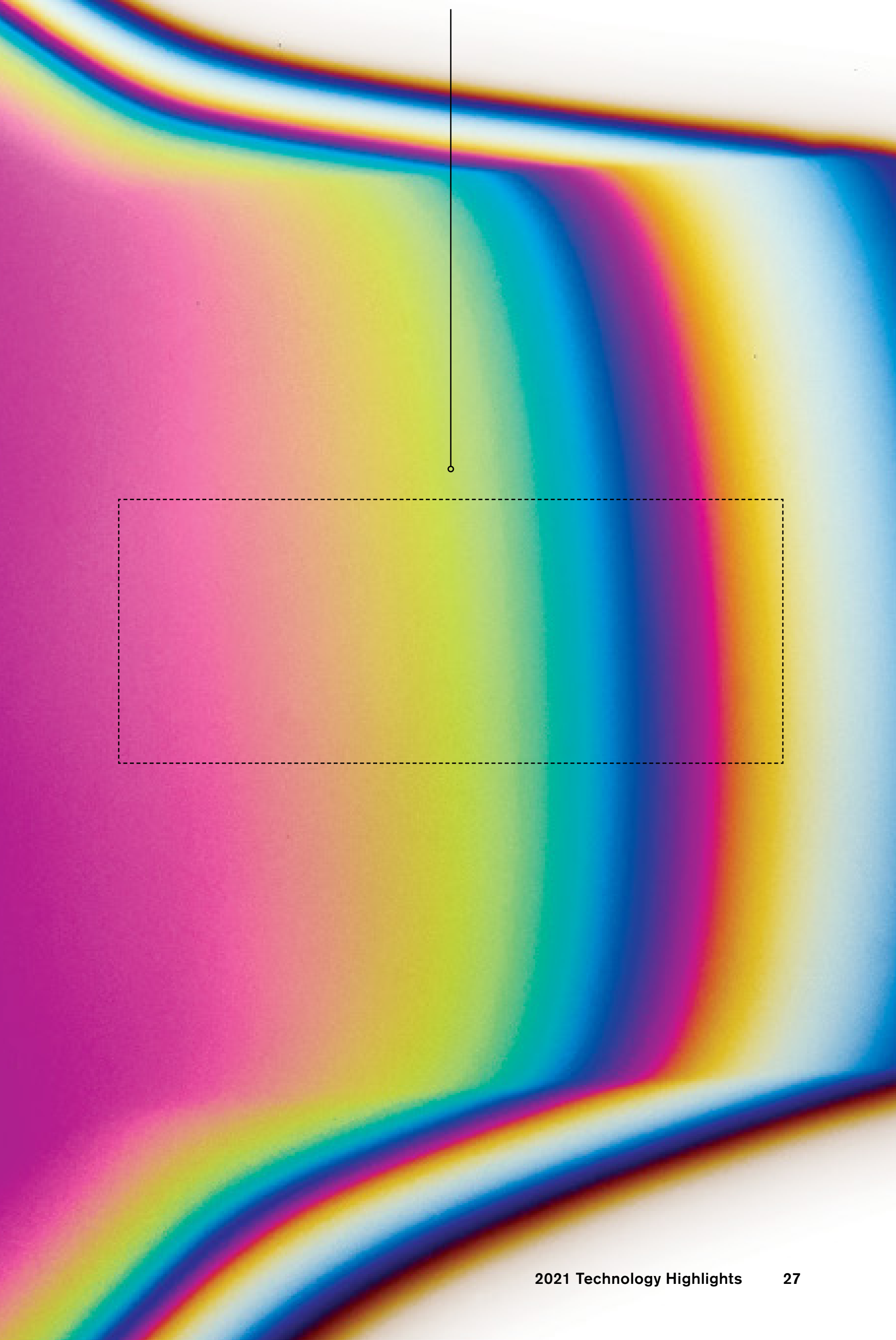
JPL is exploring sophisticated coating and filter patterning processes to create detector coatings with both “butcher-block” and gradient profiles, with each portion of the detector targeting a specific wavelength range. This approach results in a coating with either a stepwise or a gradually changing detector response from one end of the detector to the other. A related approach, using a separate gradient filter above the focal plane, is being used in the upcoming SPHEREx infrared astrophysics mission.

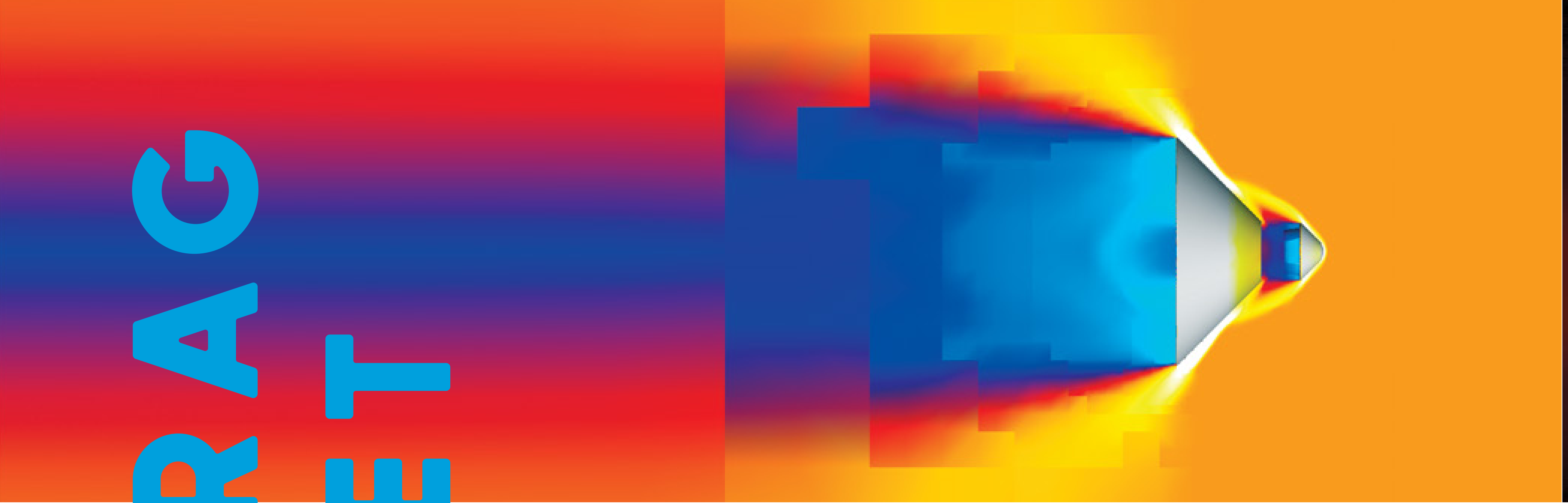
By tailoring a detector’s spatial response to match the incoming light’s spatial distribution, instrument sensitivity and throughput can be increased for all wavelengths, resulting in faster response and greater science return.

While these coatings are still in the proof-of-concept demonstration phase, samples have been successfully applied to detectors in laboratory tests. In the future, detectors using these coatings can be optimized for instruments like JPL’s Advanced Ultraviolet Imaging Spectrometer (AUVIS), an ultraviolet planetary sensor, as well as scientific and engineering instruments targeting other wavelength ranges.

ADVANCED FILTER SOLUTIONS ENABLE MULTIBAND AND BROADBAND IMAGING.

Example of a gradient filter coating enabling increased spectrometer performance across a range of wavelengths of incoming light.





DRAG NET

AEROCAPTURE—A NEW APPROACH FOR SMALLSAT PLANETARY EXPLORATION

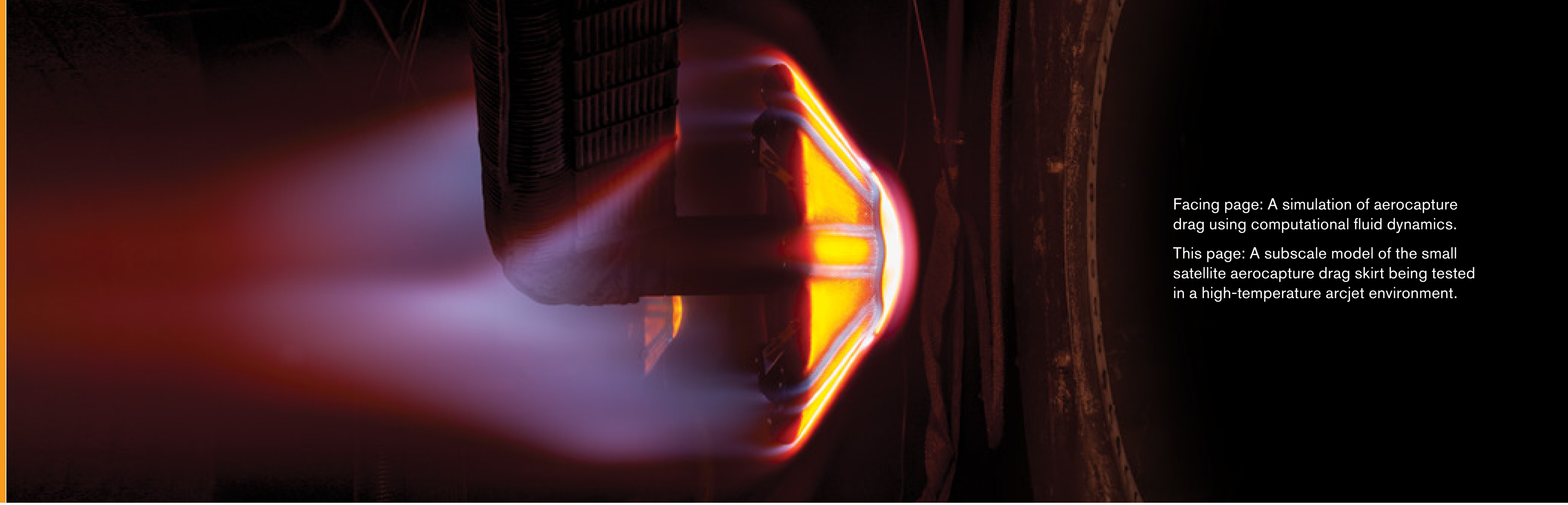
Today, there are over two dozen active spacecraft exploring the solar system and beyond. Many of these traditional spacecraft—some larger than a school bus—require many thrusters and large propellant loads for orbit insertion, trajectory maintenance, and attitude control. Newer probes and satellites, using smaller, lighter, and higher-performance components, promise to revolutionize solar system science. There are challenges, however, specifically management of limited amounts of propellant. For planetary probes in particular, the amount of propellant needed to reach a destination, "brake", and "park" into orbit can comprise most of the probe's mass.

JPL Technologists have developed a Small Satellite Aerocapture system, employing a deployable drag skirt that allows spacecraft to be slowed in a planet's atmosphere using far less propellant. This technology would allow multiple small spacecraft to be launched to several destinations while carrying more cutting-edge instrument suites for scientific observation, on par or even greater than today's larger missions. Since the target world's atmosphere helps the spacecraft slow down, propellant loads are minimized, allowing payload capacity to be increased. Small Satellite aerocapture relies on the natural forces of atmospheric drag to slow down, just like a skydiver relies upon a parachute to slow before reaching the ground. In space, however, this occurs at hypersonic speeds—over five times the speed of sound.

The key enabling technologies for Small Satellite aerocapture are a deployable drag skirt supported by guidance, navigation, and control (GNC) methods. The drag skirt must be wide enough to create drag, adjustable to the exact speed needed for orbit entry, and strong enough to withstand hypersonic velocities. Drag skirt jettison occurs at the specific time the spacecraft speed is correct for orbital capture, which requires GNC algorithms that can be executed on new computer processing systems with inputs from small sensors. Small thrusters can then fine-tune the orbit, if necessary, via autonomous control algorithms.

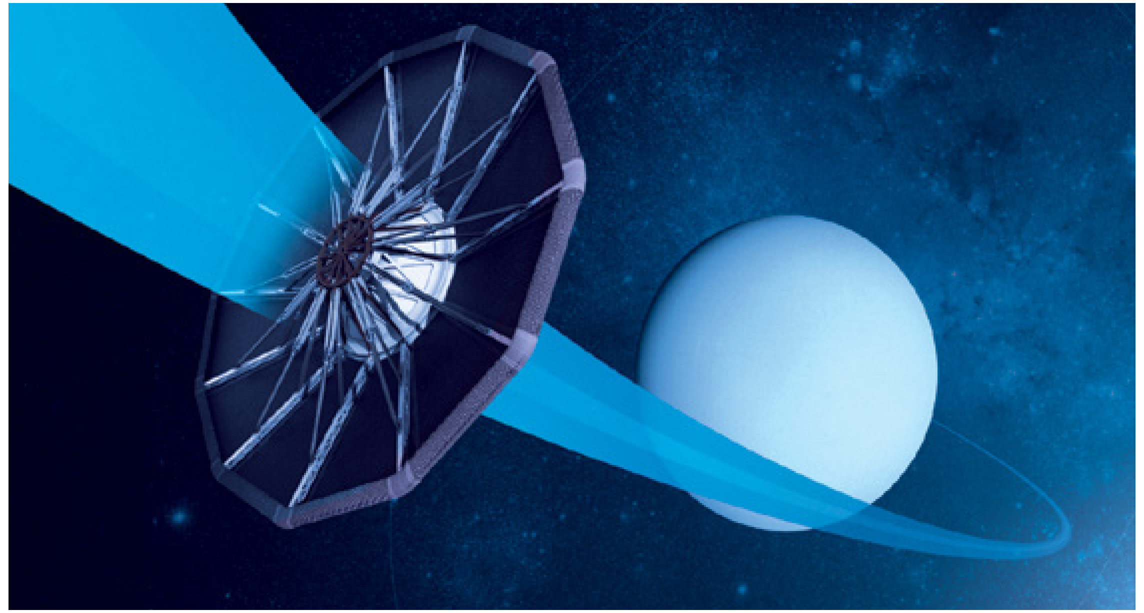
Small Satellite aerocapture can enable new capabilities in planetary exploration, including atmospheric entry probe science and broad coverage with fleets of orbiting spacecraft. Advanced computational modeling and ground-based testing has been completed and planning for spaceborne demonstration is underway. In the future, aerocapture will support greater reliability and science return as planetary satellite constellations can be regularly refreshed, and the loss of any one Small Satellite will have minimal impact on the overall mission.

PLANETARY ATMOSPHERES ENABLE SMALL SATELLITES TO MINIMIZE FUEL FOR NEW SCIENCE OBSERVATIONS.



Facing page: A simulation of aerocapture drag using computational fluid dynamics.

This page: A subscale model of the small satellite aerocapture drag skirt being tested in a high-temperature arcjet environment.



Artist's impression of a future small satellite aerocapture system deployed prior to reaching Uranus.

Electrodes consisting of numerous interdigitated metallic fingers convert electrical energy into sound waves on a silicon chip.

SCULPTING LIGHT WITH SOUND

SHAPING THE BEHAVIOR OF LIGHT ON A SILICON MICROCHIP

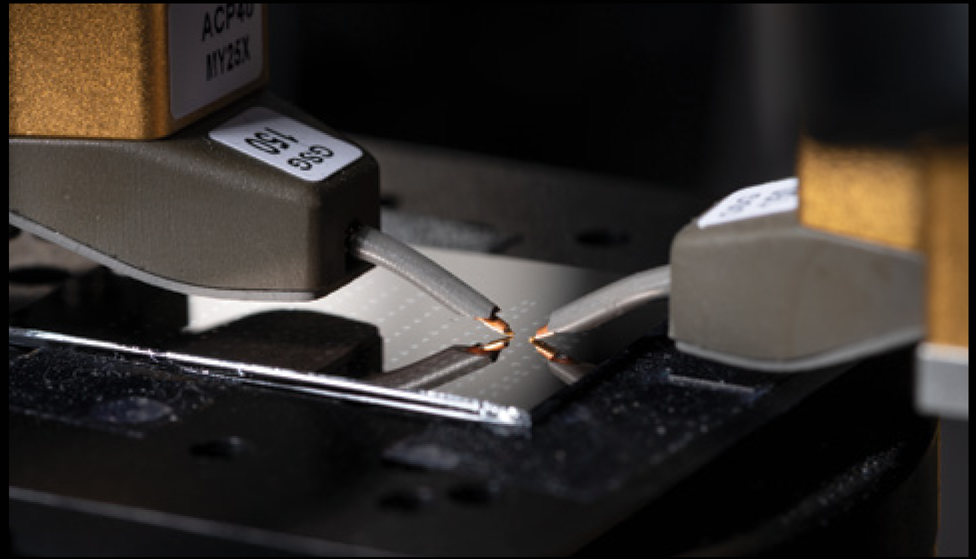
Just as semiconductors revolutionized spaceflight in the Space Age, so are photonic (light-driven) semiconductors poised to revolutionize space exploration in the 21st century. These ultra-compact, low-energy, robust devices can serve a wide variety of critical investigative functions on spacecraft.

As impressive as this technology is, however, the miniaturization of some photonic components has been difficult. A new technology, being investigated at JPL, shows promise: acousto-optic interactions. This technology uses tiny audio transducers implanted on the photonic chip to alter and control the characteristics of the light within the chip, akin to electronic manipulation of electrons on a traditional integrated circuit chip. A hypersonic (very high frequency, above what humans can hear) signal is directed from the transducer to the optical waveguide—essentially, a conduit for light—physically deforming the waveguide material. Changing the physical characteristics of the waveguide allows its functions to be controlled, permitting, among other things, the assured one-way travel of photons within the pathway for on-chip laser applications—back reflection has been a problem in such devices.

This technology is platform agnostic and is applicable across a range of photonic microchip implementations. While silicon was used for this demonstration, other materials should be equally usable as the application requires. This technology is applicable to visible, infrared, and ultraviolet wavelengths, as necessary, for a variety of outcomes.

ACOUSTO-OPTIC TECHNIQUES MINIATURIZE AND ADVANCE PHOTONIC CIRCUIT DESIGN FOR APPLICATIONS SPANNING QUANTUM INFORMATION CONTROL TO SIGNAL PROCESSING.

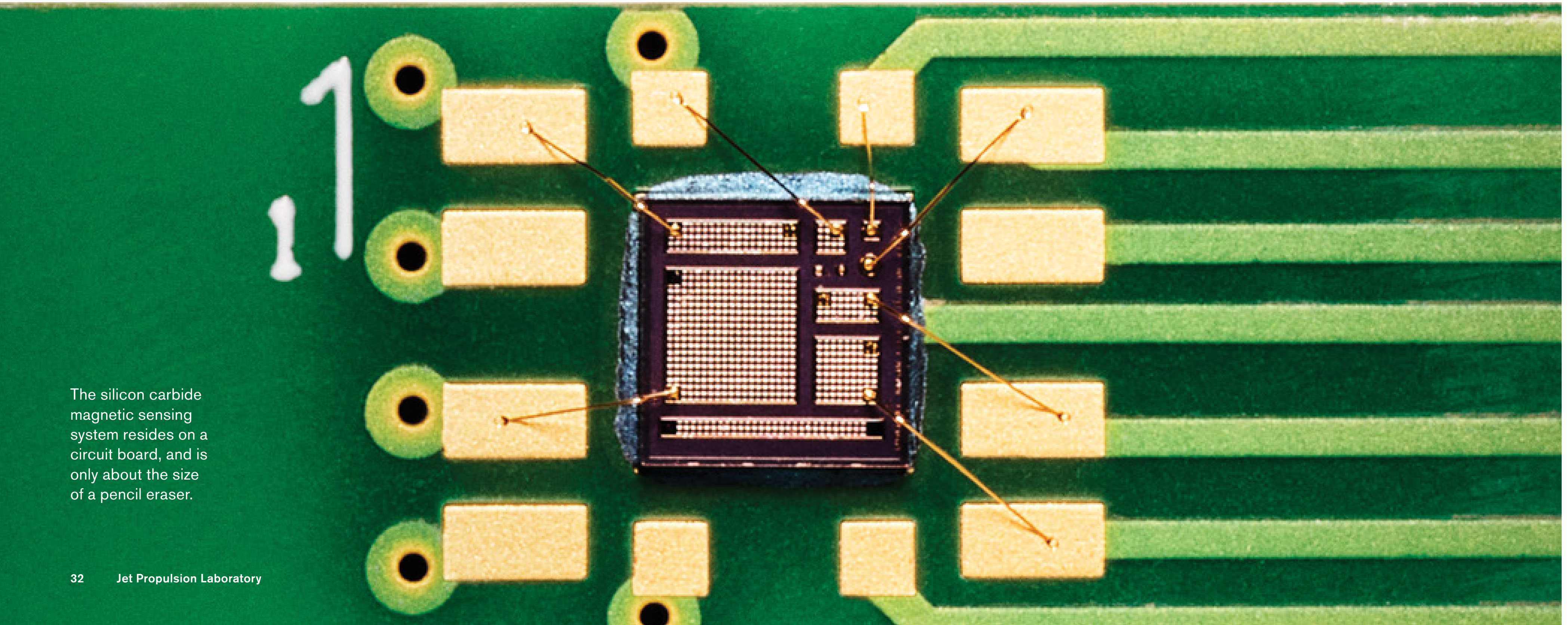
Acousto-optics technology not only improves the performance of the chip dramatically, but also results in up to a 100-times reduction in component size. This consequently reduces mass and, in many cases, complexity, resulting in smaller, lighter, and less power-hungry spacecraft instrumentation. Potential applications include optical sensing, better lidar devices, and improved laser communications. They may also increase the diversity of wavelengths available within photonic chips, which will find applications in defense and commercial applications as well as planetary science. More science with smaller, less massive components, requiring less power, will be the net result, drawing great questions about the solar system and beyond ever closer to answers.



Right: Microwave probes are used to test hundreds of prototype devices on a single microchip.

MAGNETIC PERSONALITIES

USING MAGNETIC FIELDS TO UNDERSTAND THE MOON'S INTERIOR

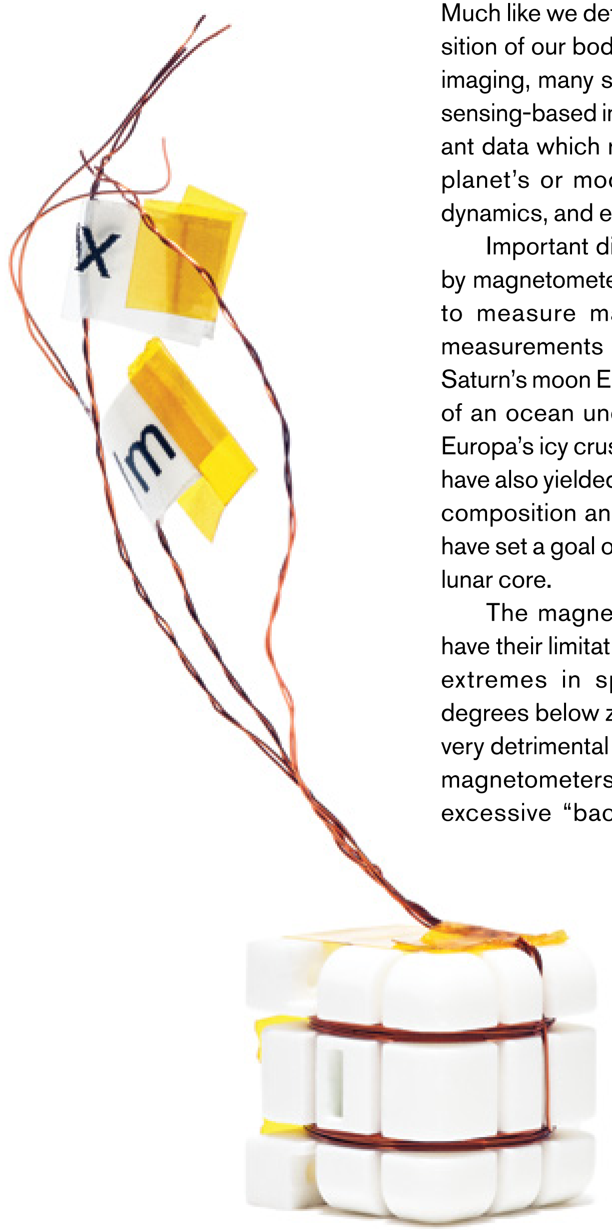


The silicon carbide magnetic sensing system resides on a circuit board, and is only about the size of a pencil eraser.

One way we learn about other worlds is to measure their magnetic field signatures. Much like we determine the internal composition of our bodies with magnetic resonant imaging, many space probes use magnetic sensing-based instruments to gather important data which reveals information about a planet's or moon's interior composition, dynamics, and even evolution.

Important discoveries have been made by magnetometers, the instruments we use to measure magnetic fields, including measurements of the vaporous plumes of Saturn's moon Enceladus and the prediction of an ocean underneath the Jovian moon Europa's icy crust. Magnetic measurements have also yielded secrets of our own Moon's composition and structure, and scientists have set a goal of scanning all the way to the lunar core.

The magnetometers currently in use have their limitations, however. Temperature extremes in space, from hundreds of degrees below zero to hundreds above, are very detrimental to instrumentation. Modern magnetometers also struggle to filter out excessive "background noise" from the spacecraft or plasma currents which contaminate the measurements, making it difficult to draw exacting conclusions.



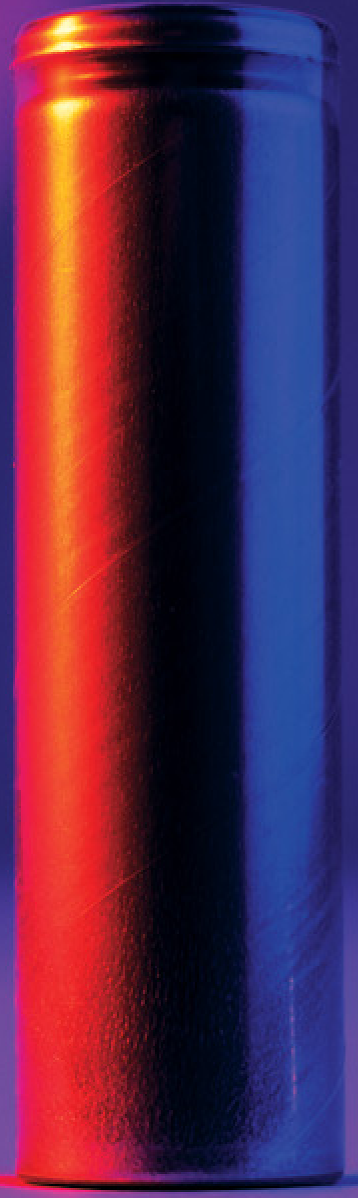
A 3-axis, 3D printed Helmholtz coil used for magnetic field modulation and field nulling.

SiCMag could enable a series of distributed magnetic field measurements made on the lunar surface to provide insight into the Moon's extinct self-sustaining dynamo, thus providing clues into its magnetic history and composition.

NEW, ULTRA-SMALL QUANTUM MAGNETOMETERS: A REVOLUTIONARY TOOL FOR PLANETARY SCIENCE.

JPL is prototyping a new magnetometer called the silicon carbide magnetometer or SiCMag, which uses a solid-state sensor made of a silicon carbide (SiC) semiconductor. Inside the SiC sensor are quantum centers—defect irregularities at an atomic scale—that exhibit a response to the presence of an external magnetic field, resulting in an electrical current that can be measured. This new technology is incredibly sensitive, and due to its large bandgap, is capable of operating across a wide range of temperature extremes and harsh radiation environments commonly encountered in space. SiCMag is also very small—about the size of a penny—so many can be flown with far less mass than heritage magnetometers, which allows for infusion on smaller spacecraft like nano- or picosats. Additionally, SiCMag has the ability to potentially self-calibrate due to its absolute sensing capability, which is a significant advantage in the remoteness of space

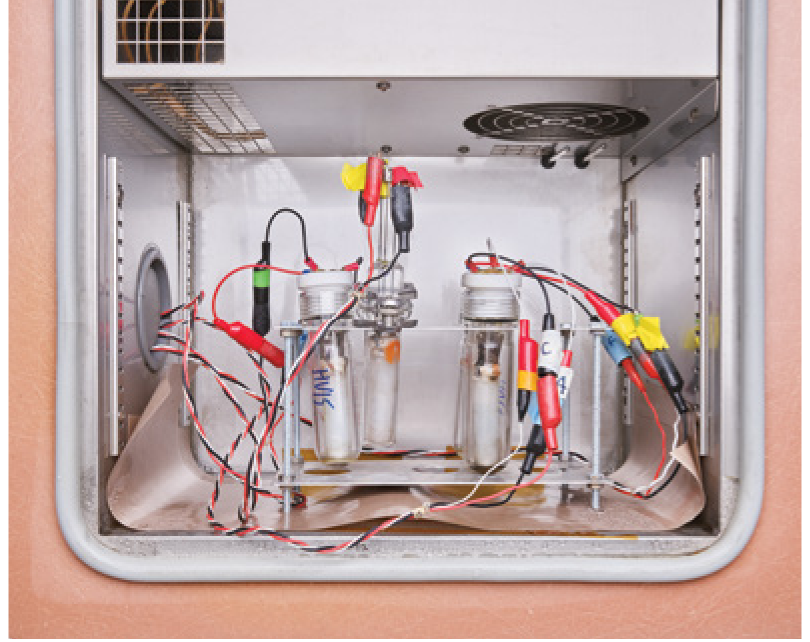
Thanks to their low mass, low power requirements, and robust nature, an armada of SiCMag devices could be deployed around Earth's Moon, enabling the first global magnetic investigation of our nearest neighbor's internal structure. This is just one example of the many ways that SiCMag will open new frontiers in planetary science.



These small lithium-ion (Li-Ion) batteries can operate at -40°Fahrenheit (-40 Celsius) and below, and have demonstrated the ability to deliver nearly 40 percent more energy than the state-of-the-art batteries on the Mars InSight lander.

POWERING THROUGH THE NIGHT

HIGH BATTERY PERFORMANCE AT LOW TEMPERATURES



The electrochemical characteristics of electrolytes are studied in experimental 3-electrode cells.

Spacecraft exploring the cold reaches of the solar system face many challenges, and one of the most significant is power. Batteries hate the cold, and while one might think of places like Europa and Neptune as being frigid, temperatures also get quite chilly on the Moon and Mars as there is little to no atmosphere to mitigate extremes. In such regions, battery performance degrades, and spacecraft must use some of their power to keep their batteries heated, leaving less energy for critical scientific goals.

JPL is addressing this problem with new, cutting-edge electrolytes aimed at improving the low-temperature performance of lithium-ion (Li-Ion) batteries—the batteries of choice for most space applications. While total energy storage capacity of commercially available Li-ion batteries is only slightly affected by temperature, their power, or discharge rate, starts to decline sharply below 14 degrees Fahrenheit (minus 10 Celsius), and is severely degraded at minus 40 Celsius—temperatures common in space environments. JPL's new electrolyte chemistries, which are composed of mixtures of organic and lithium compounds, offer high energy storage capacity, excellent power, and increased duty cycles at temperatures as low as minus 76 degrees Fahrenheit (minus 60 Celsius). These new electrolytes allow for smaller battery cells as well, which offer better safety characteristics, improved low-temperature performance, and require less battery system monitoring than larger sizes. This new electrolyte technology is being incorporated into the Europa Clipper mission now scheduled for flight in 2024.

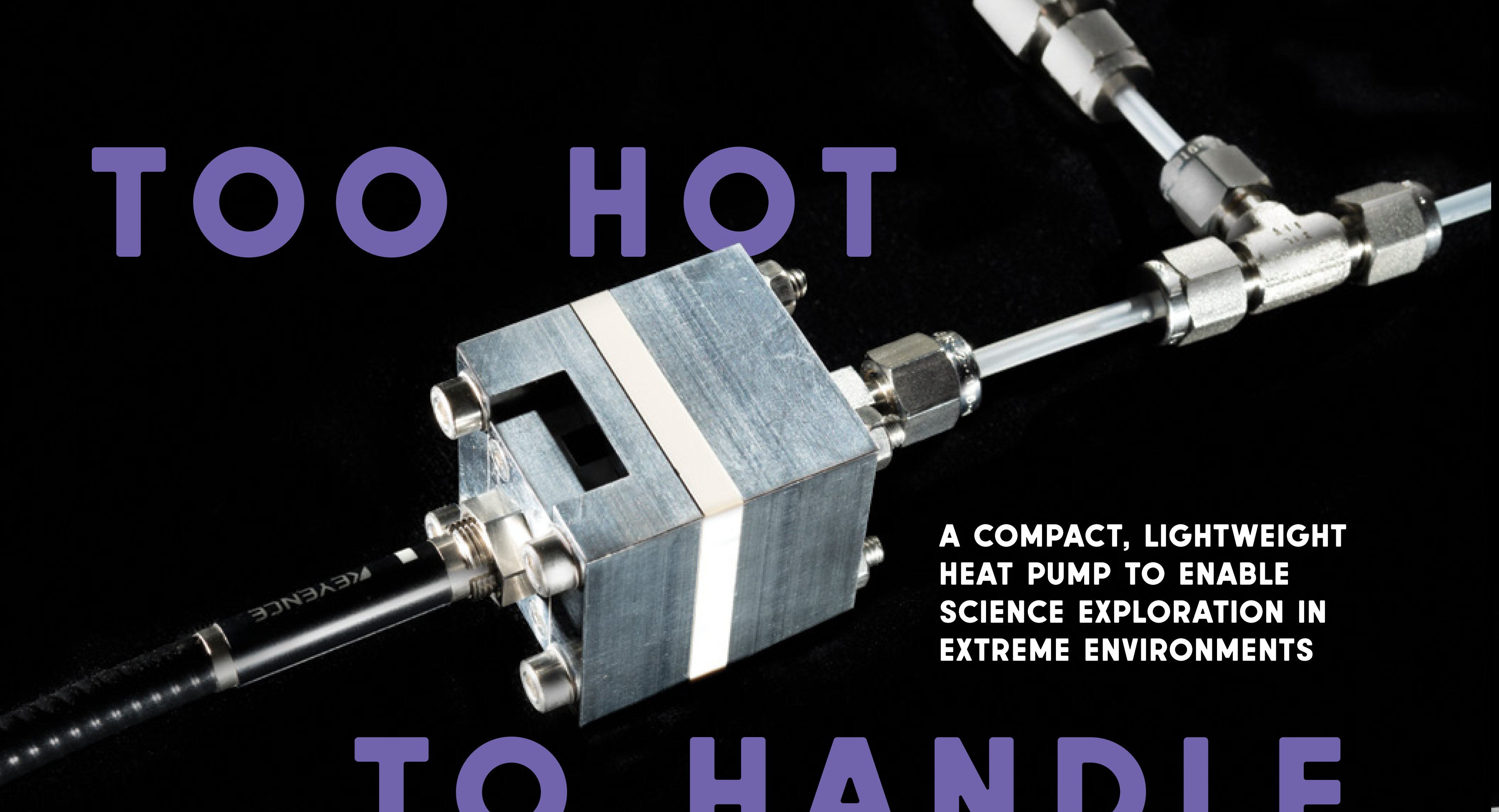
ADVANCES IN LI-ION BATTERY CHEMISTRY SIGNIFICANTLY IMPROVE THEIR PERFORMANCE IN SPACE AND ON COLD PLANETS AND MOONS.

The impact of improved cold-temperature batteries cannot be overstated—any target in the solar system, even Earth orbit, experiences harsh temperature extremes. In these situations, the biggest enemy is severe cold—power is truly a mission-defining resource. And while spacecraft instrumentation continues to get smaller and less power-hungry, every spacecraft—whether nuclear powered or using solar panels—requires robust battery systems to function. Improving their energy retention and duty cycles will offer huge gains in planetary exploration.

Custom low temperature Li-ion battery electrolytes are prepared in environmentally controlled glove boxes.

TOO HOT TO HANDLE

A COMPACT, LIGHTWEIGHT HEAT PUMP TO ENABLE SCIENCE EXPLORATION IN EXTREME ENVIRONMENTS



A fast-response check-valve prototype, critical to enabling a heat pump with low mass (less than 0.75 kg excluding radiator mass), to achieve 100 watts of cooling with less than 45 watts of electrical input power.

Venus is a hot place, and not just in the way we think of a hot day on Earth, but hot as in about 900 degrees Fahrenheit on the surface. That's hot enough to melt lead. And while the upper atmosphere is temperate at altitudes above 60 miles (100 kilometers), exploring lower regions of the atmosphere is challenging due to electronics-destroying temperatures of well over 200 degrees F (93 C). Overall, Venus is the blowtorch planet of the solar system.

Early probes to Venus had very limited cooling abilities and consequently short operating lives when exposed to the Venusian environment. But new cooling systems being pioneered at JPL promise to offer protection to the increasingly sensitive, high-tech instrumentation that will be sent there later in this decade. JPL's tiny heat pump, not dissimilar to a miniaturized version of the technology that cools modern buildings, will allow spacecraft to explore the lower regions of the Venusian atmosphere down to about 28 miles (45 km).

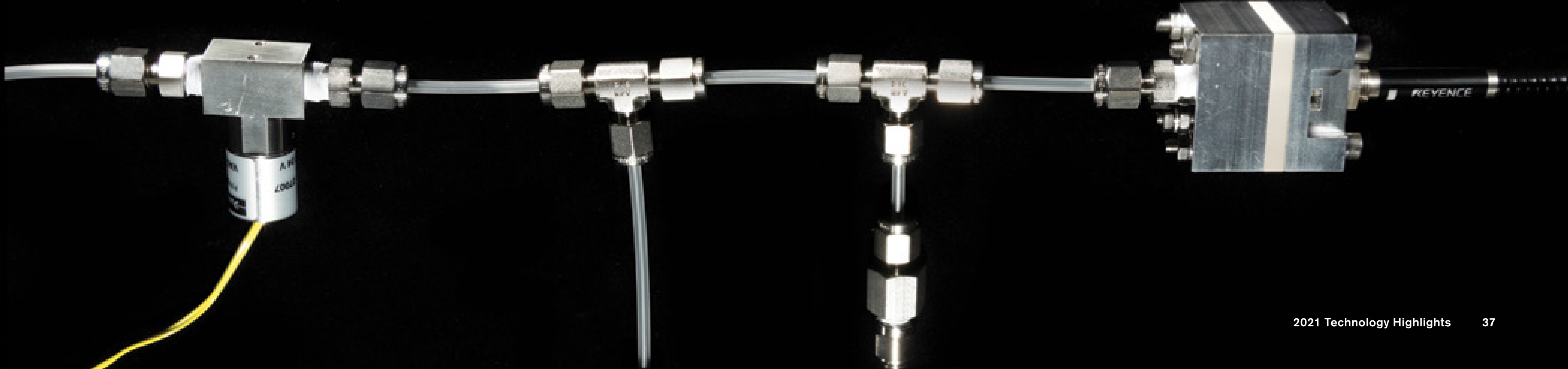
This advanced cooling system utilizes a miniaturized, high-speed, linear (as opposed to the more conventional rotary) compressor that draws very little power and is highly reliable. It also generates very little vibration, important when working in concert with sensitive instrumentation (we've all felt the vibrations when an air conditioning unit kicks on). The development of this linear pressure wave generator leverages existing technologies that have been developed for spaceflight-rated Stirling cryocoolers.

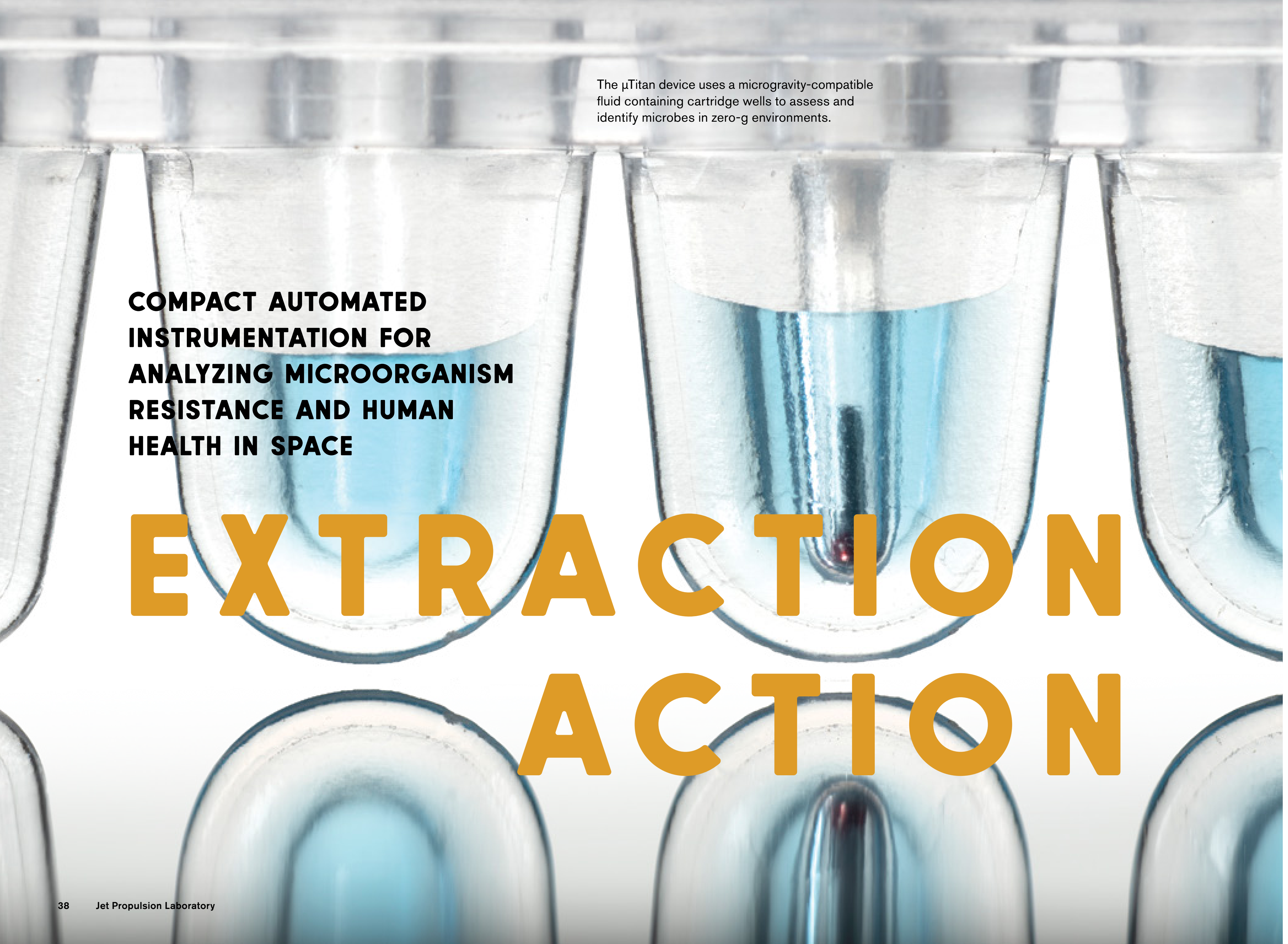
The dual-opposing pistons that serve to compress the refrigerant have very low exported vibration, and can operate at a frequency above 100 hertz for high power density and efficiency. The pistons are supported by flexure bearings that eliminate mechanical wear. The necessary check valves are of a unique design that reduces flow resistance when opened and minimizes leakage when closed, increasing the compressor's efficiency. The valves also use unique materials to minimize mechanical impact stresses and enhance the life of the system.

This compact heat pump will increase science return for a broad range of future NASA space missions. It can also be applied to a wide range of medical and commercial applications such as safe transportation of life-saving medicines, vaccines, and biological samples in remote areas on Earth.

A MINIATURIZED HEAT PUMP WILL ENABLE BOTH LONG-DURATION SCIENCE MEASUREMENTS ON VENUS BELOW CLOUD-LEVEL BALLOON FLIGHT, AND LOW-LATITUDE DAYTIME LUNAR SURFACE EXPLORATION IN LOW LATITUDE REGIONS.

Testing setup to check valve displacement and response time. The solenoid valve (far left) introduces a pressure pulse to open the check valve where the laser (far right) measures the valve flap displacement.

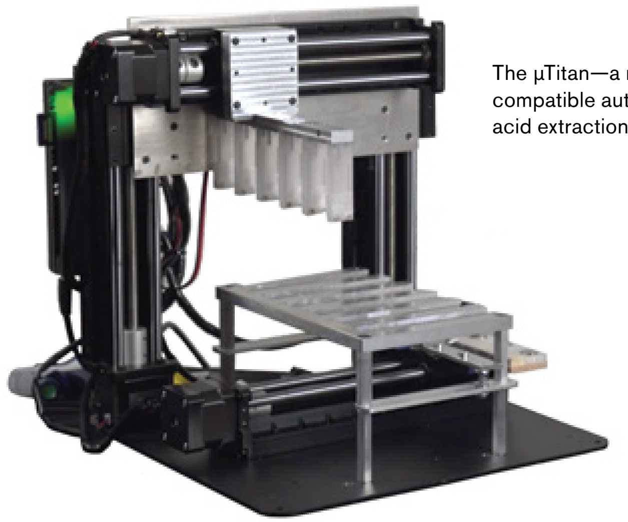




The µTitan device uses a microgravity-compatible fluid containing cartridge wells to assess and identify microbes in zero-g environments.

COMPACT AUTOMATED INSTRUMENTATION FOR ANALYZING MICROORGANISM RESISTANCE AND HUMAN HEALTH IN SPACE

EXTRACTION ACTION



The µTitan—a microgravity compatible automated nucleic acid extraction system.

Some microbes get stronger in space—in some cases, microgravity releases their superpower. Not all of them are friendly, and some nasty germs have even become more virulent aboard the International Space Station, sounding an alarm for long-duration spaceflight. We must learn as much as we can about the behavior of these organisms in space before undertaking long-duration stays in the vicinity of the moon or heading off to Mars with crews.

REDESIGN AND MINIATURIZATION OF EXISTING GROUND-BASED DNA EXTRACTION TECHNIQUES PERMITS ON-ORBIT MICROORGANISM SAMPLE ANALYSIS REDUCING PROCESSING TIME FROM MONTHS TO HOURS.

Today, detecting potentially harmful microorganisms to assess crew health aboard the ISS is a three-to-six-month process. Manual sample processing protocols for nucleic acid extraction, and the time taken to return samples to Earth for ground-based processing, call for a faster and more automated approach.

Currently, automated extraction technologies are too delicate, too large, and not suited to the zero-G conditions necessary for operation on the space station. But a team of JPL researchers, engineers, and outside collaborators are developing a solution. They have modified the shape and size of the containers used in the extraction of nucleic acids, and in doing so changed the way the fluid samples behave in zero-G. The compact device, which has been miniaturized and ruggedized for spaceborne use, relies upon the surface tension of liquid, rather than gravity, to control the flow of the sample. The resulting technology has been dubbed the Microgravity (µ) Tolerant InsTrument for Automated Nucleic-acid extraction, or µTitan.

To date, µTitan has been field tested in harsh Earth environments and on zero-G parabolic test flights. Not only did µTitan pass these tests, but it also delivered completed samples, processed automatically, in less than four hours. In addition to examining dangerous germs, µTitan can also evaluate human DNA samples to track damage from long-term or sudden radiation exposure during spaceflight. It may also evolve to support health care in remote locations here on Earth or monitoring of the microbiome of future lunar and Martian habitats.

If we wish to truly reach the stars, we will need to stay healthy in the process, and technology such as µTitan is one important step in that process.

The µTitan instrument being tested in a microgravity flight.

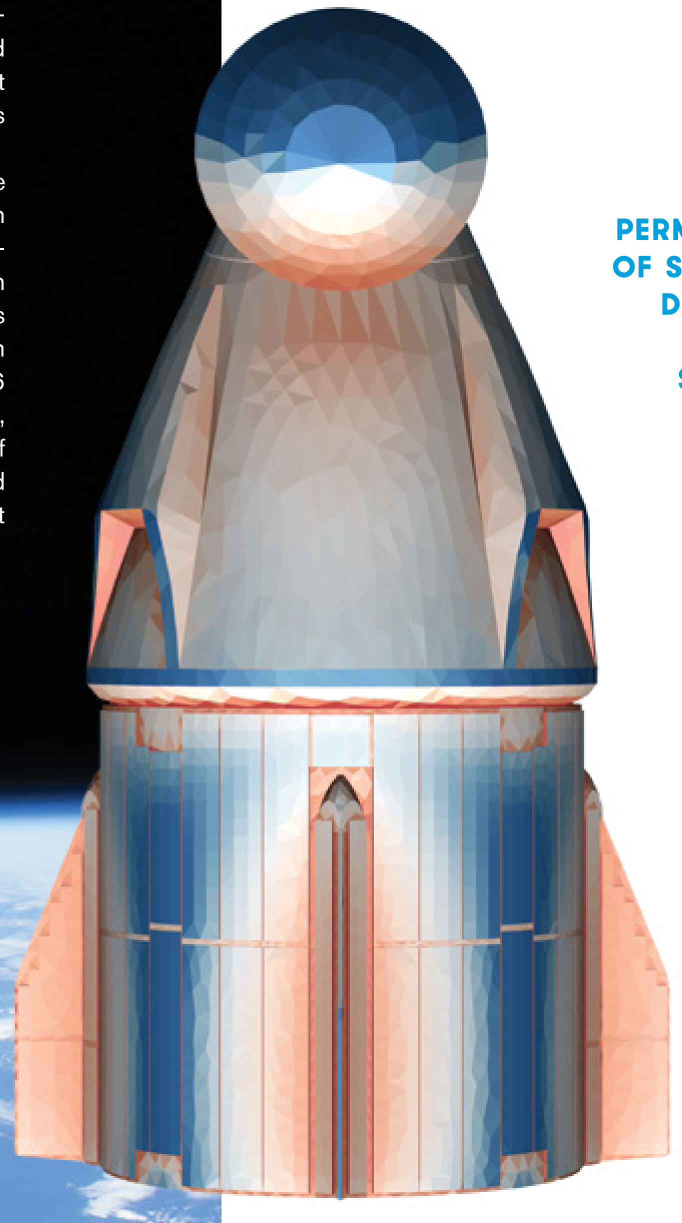
POWER PLAY

MODELING SOLAR ARRAY PERFORMANCE UNDER SPACE ENVIRONMENT EFFECTS

View of a SpaceX Crew Dragon docked with the International Space Station. New solar panel materials were tested during the multi-month mission, validating the calculations of JPL's innovative degradation-predictive software.

When we think of long-duration space missions, many things come to mind… the need for extended power generation, navigation, radiation effects, mechanical and electronic reliability are just a few. But what about surface contamination? As it turns out, that's a factor as well.

Over time, components exposed to the harsh environment of deep space can begin to release gases, and these can contaminate lenses, sensors, and solar panels. With a hard vacuum tugging on material surfaces and temperature extremes ranging from minus 482 degrees Fahrenheit (minus 286 Celsius) to minus 364 F (minus 220 C), spacecraft surfaces can emit all kinds of contaminants. Over the course of years and decades, this can dramatically impact mission objectives.



While the extent of outgassing can be tested in laboratories on Earth, these tests are not perfect. To manage outgassing, many spacecraft rotate with respect to their solar orientation, but outgassing rates can change over time. In addition, different materials outgas at varying rates, making prediction quite a problem.

NEW TOOLS PERMIT ANALYSIS OF SOLAR ARRAY DEGRADATION FOR HUMAN SPACEFLIGHT.

JPL technologists have created time- and temperature-dependent software models that allow more accurate and detailed predictions of long-term outgassing across various materials. These models have proven to be highly accurate at determining the rate of solar panel performance decline, which is crucial to the long-term health of most spacecraft, including those designed for human crews. JPL software was used to profile the long-term effectiveness of the solar panels on SpaceX's Dragon capsule, which can remain docked at the international Space Station for as long as six months. Model predictions were confirmed via the recent Demo-1 mission to the ISS. Other missions evaluated with the software include the Psyche, SPHEREx, Mars Sample Return, and the Nancy Grace Roman Space Telescope Coronagraph Instrument.

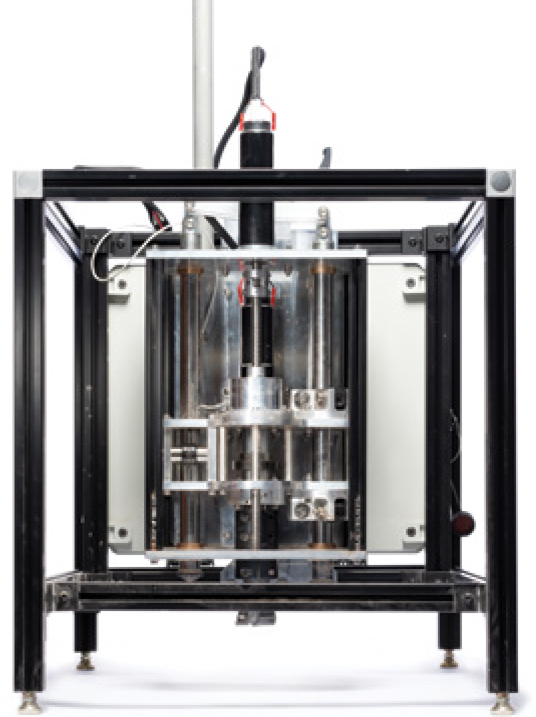
In the future, such modeling will be important for long-duration spaceflight, such as crewed missions to Mars, where component reliability will be critical to mission success.

Simulation results illustrate which solar array sections are most susceptible to contamination on the SpaceX Crew Dragon. These results are then combined with material outgassing rates and absorption spectra to determine the resultant solar array performance degradation.

A close-in view of the abrading drill bit, which can characterize the firmness of soil surfaces before the rover drives across them.

MIND THE GAP

DOUBLE DUTY: PERSEVERANCE'S ABRADING BIT TOOL CAN ALSO MEASURE TERRAIN STRENGTH



A testbed for the abrading drill bit.

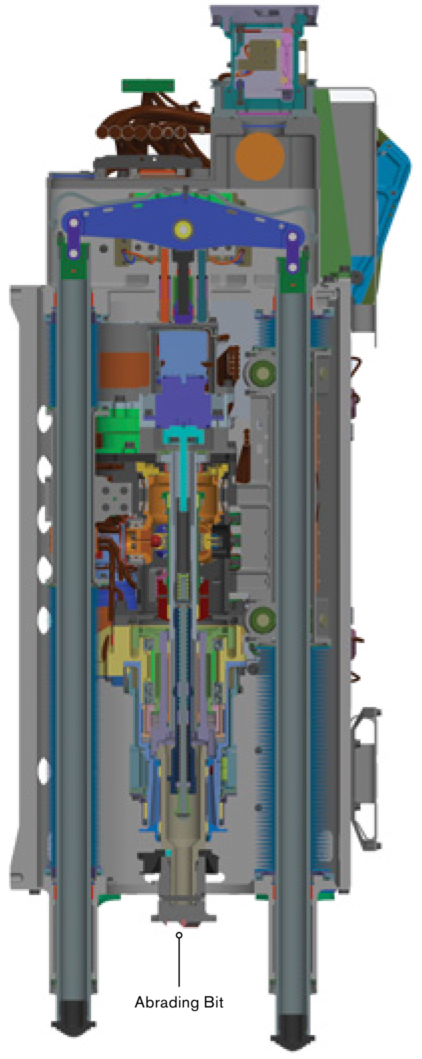
The job of a Mars rover is a tough one. As Perseverance and Curiosity navigate the Martian surface, all kinds of traps await… loose sand, slopes, and gravel can all conspire to ensnare a rover. We witnessed this with the MER rover Spirit, which ended its brilliant career in a sand trap—a testament to the difficulty of understanding Martian terrain using imagery alone. Spotting and identifying these hazards is currently done manually by rover teams using their best intuitive judgement to make decisions about the path ahead. As a result, rovers such as Perseverance drive very slowly and cautiously. As Mars rovers embrace increasingly ambitious goals, resolving these uncertainties will become ever more critical to success.

TECHNOLOGY ADD-ONS TO AN EXISTING TOOL ALLOWS MECHANICAL STRENGTH AND SPATIAL VARIATION OF MARS TERRAIN TO BE KNOWN.

Having the capability to characterize terrain ahead of the rover would allow for faster driving and more science. To accomplish this, a new ground-truth measuring capability is in the works at JPL, using technology already present on the Perseverance rover. One of Perseverance's drill bits, called the abrading bit tool, is strikingly similar to a device called a Bevameter, a tool commonly used to collect geotechnical data to assess terrain traversability on Earth. JPL technologists, utilizing a duplicate of Perseverance's abrading bit tool, demonstrated that terrain strength measurements are possible.

A prototype that mimics Perseverance's onboard toolset was built using off-the-shelf components. Besides the drilling hardware, a data-processing pipeline was developed to convert raw measurements into an assessment of soil strength. Tests were performed on four Mars-like simulants with different mechanical properties. These tests demonstrated that the abrading bit is capable of making shear and bearing strength measurements, which would allow Perseverance to perform geotechnical analysis using an existing onboard instrument to enhance mission safety.

In the future, this methodology may be useful on other mission targets, such as the icy moons of the outer planets, home to some of the most uncertain terrain in the solar system. It's a classic win-win scenario: repurposing existing, flown instruments to enhance the safety of the spacecraft.



Cutaway CAD rendering of the entire drill system.

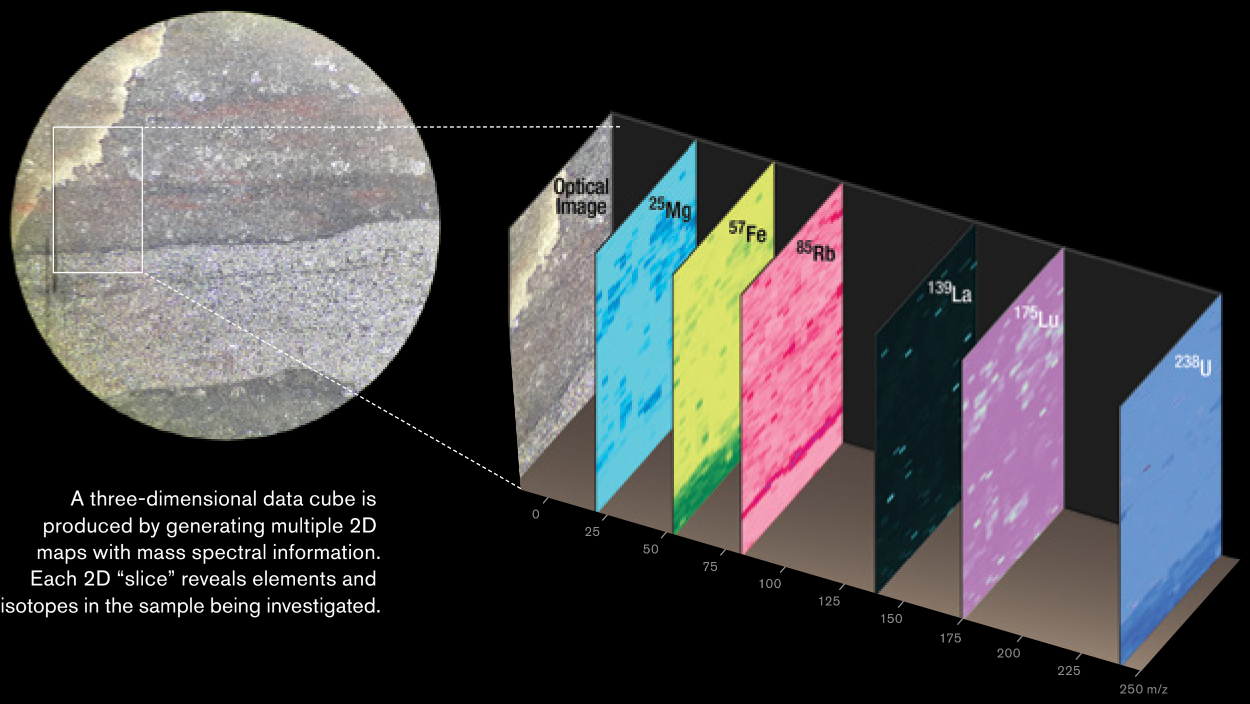
UNDERSTANDING THE GEOLOGIC TIMELINE OF THE SOLAR SYSTEM

ROCKS OF AGES

Plasma formed during lab-based testing of a miniaturized laser ablating a sample to determine its elemental composition.

To understand the formation and evolution of our solar system, knowing the age of geological formations on other worlds is critical. On Earth, we rely on the measurement of radioactive materials in rocks to judge their age by measuring the radioactive decay of known elements, a technique known as radiometric dating. But this technique traditionally utilizes large, power-hungry ground-based laboratory instruments. To accomplish these kinds of measurements in planetary missions, new technology is required that is smaller, lighter, and requires less power, yet can still deliver similar results.

Dating results are more accurate when the radioactive decay of different elements is measured and compared, but the need for comparison within a sample complicates the dating process. A successful flight dating instrument will need to identify and distinguish individual elements and their isotopes as well as their relative quantities. Since samples may have different elemental mixtures and may have crystals of different mineralogy in different regions, it's also important to know where the isotopes originated in the sample. Until now, instruments with these combined capabilities have remained out of reach.



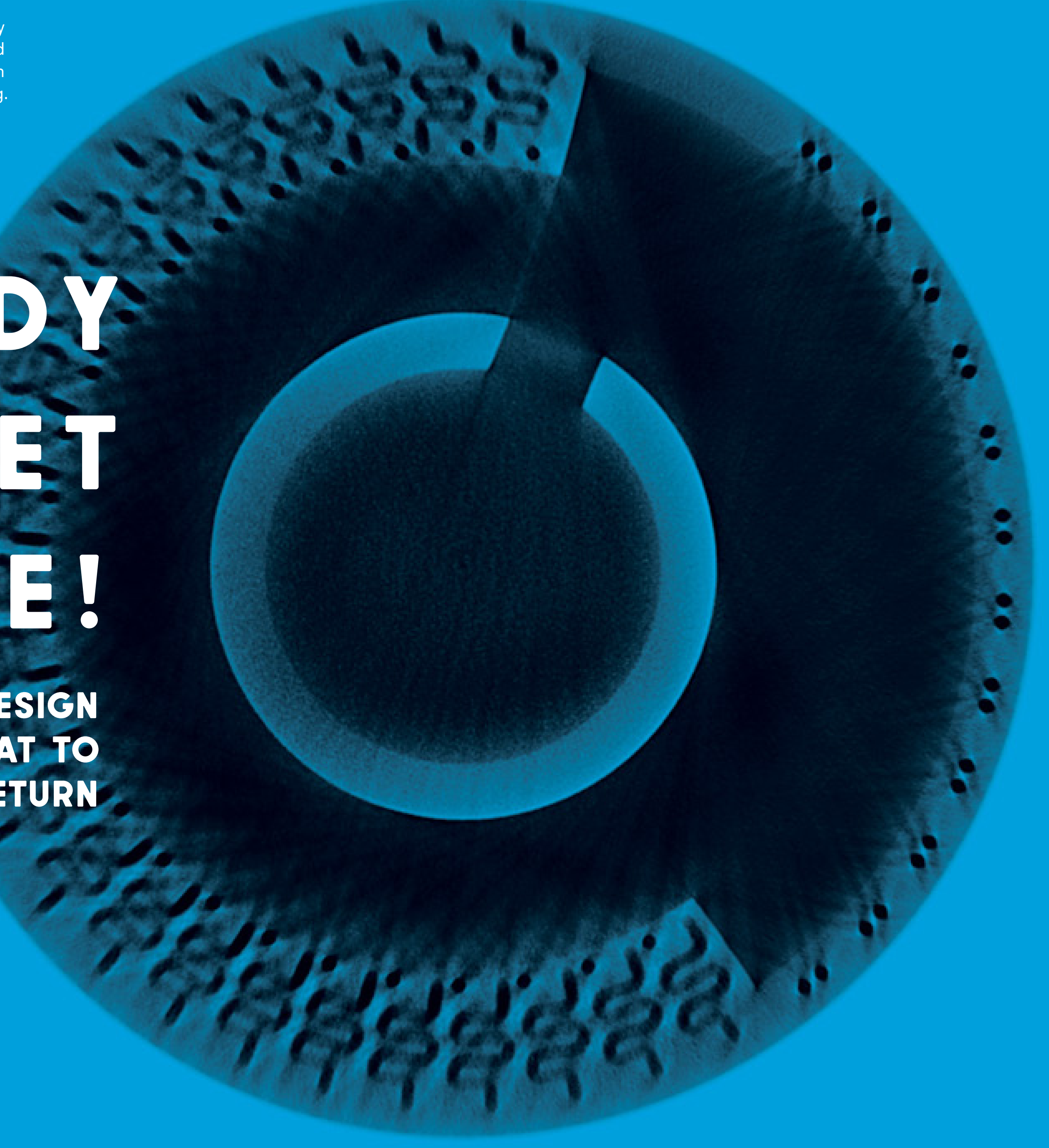
A three-dimensional data cube is produced by generating multiple 2D maps with mass spectral information. Each 2D "slice" reveals elements and isotopes in the sample being investigated.

JPL, working in association with Caltech, is developing a lightweight, lower power in-situ measurement technique called Mass Spectral Imaging (MSI) to distinguish and locate elemental isotopes within rock samples. In the MSI technique, a small laser scans the sample in steps, ablating (or eroding) the sample surface with a laser pulse at each step. The ablation process generates a gas that is fed into a mass spectrometer, which separates the gas particles accord-ing to their atomic numbers and masses, allowing the elements and isotopes to be determined. When combined with the ablation locations, this provides both mineralogical and isotopic data that can be compared to precise baseline measurements made in laboratories on Earth.

The MSI Instrument is being calibrated using a meteorite of Martian origin that has a well-known isotopic composition.

Spacecraft that incorporate lightweight, compact, and energy efficient MSI technology will advance our understanding of the ages of rocky bodies in our solar system, as well as their origins. It's one more important step toward forming a holistic view of the solar system and our place in it.

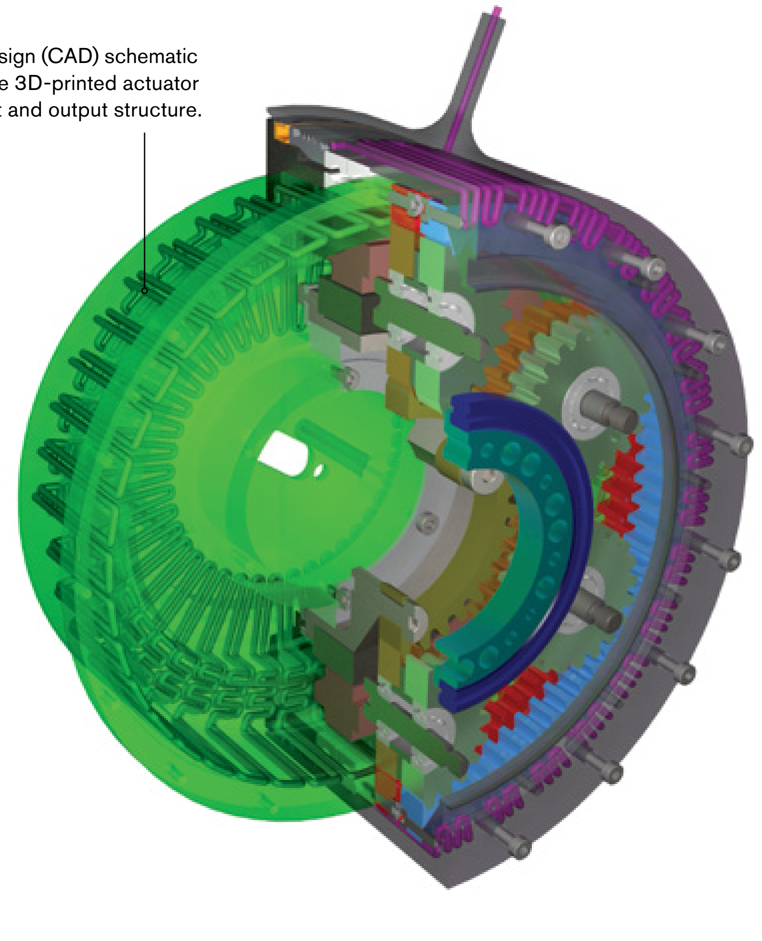
NEW INSTRUMENT TECHNOLOGY BASED ON MASS SPECTRAL IMAGING WILL GIVE NEW INSIGHTS INTO GEOLOGICAL PROCESS TIMELINES OF ROCKY BODIES.



CT scan of actuator assembly with embedded 3D printed Oscillating Heat Pipe design enabling faster gearbox heating.

READY SET ACTUATE!

A NEW ACTUATOR DESIGN USES WASTE HEAT TO IMPROVE SCIENCE RETURN



Computer Aided Design (CAD) schematic view of the 3D-printed actuator assembly input and output structure.

Robots on Mars just don't get a break—the environment ranges from chilly during the day to downright sub-freezing at night. Since the Martian atmosphere is extremely thin, it does not retain much heat, and while the average temperature is about minus 80 degrees Fahrenheit (minus 60 Celsius), nighttime temperatures can range from minus 100 F (minus 73 C) at the equator to almost minus 200 F (minus 125 C) near the poles. It's a lot to endure.

Like Earthly explorers, robots on Mars rely extensively on their manipulators (the robotic equivalent of arms and hands) to get work done, and the Martian equivalent of frostbite can inhibit their activity. Currently, the robots must wait until well after sunrise to start as their mechanical hands slowly warm enough to be fully functional—lubricants get very sticky at these low temperatures, reducing lubricity and inhibiting movement.

Technologists at JPL are investigating mechanical warming systems to overcome this delay and enable more science during longer periods. These new actuator assemblies incorporate 3D printing to add narrow, serpentine heat transfer passages from the motor into the actuator gearbox, allowing for much quicker gearbox heating when it's time to go to work.

Even in these low temperatures, once the mechanical arm and gripper are working the reverse problem can rear its head—excessive heating. Changing the design of the actuator architecture not only allows for quicker heating, but helps to shed waste heat by allowing rapid cooling through shorter thermal pathways. This integrated thermal management approach uses embedded channels via additive manufacturing to form an Oscillating Heat Pipe (OHP). This can increase thermal conductivity by 100 times with a 10 times improvement in actuator power density.

A 3D PRINTED ACTUATOR DESIGN SOLVES THERMAL MANAGEMENT CHALLENGES FOR MISSIONS TO OCEAN WORLDS.

Continuing design work should result in greatly improved heating and cooling efficiency and better use of available energy, offering much more bang for the buck in power utilization with greater science return in surface investigations. Future Ocean Worlds missions can not rely upon the environment for heating of actuators, so this technology represents an enabling capability where rapid sampling and high power density mechanisms are required.

A Surface Acoustic Wave diffraction grating with a series of gold electrodes that are only 5.5 micrometers in length. The entire device is only a few hundred micrometers in length, comparable to the 100 micrometer diameter of a human hair.

SPECTRAL SOUNDS

SEEING THE UNIVERSE ACROSS MULTIPLE FREQUENCIES OF LIGHT

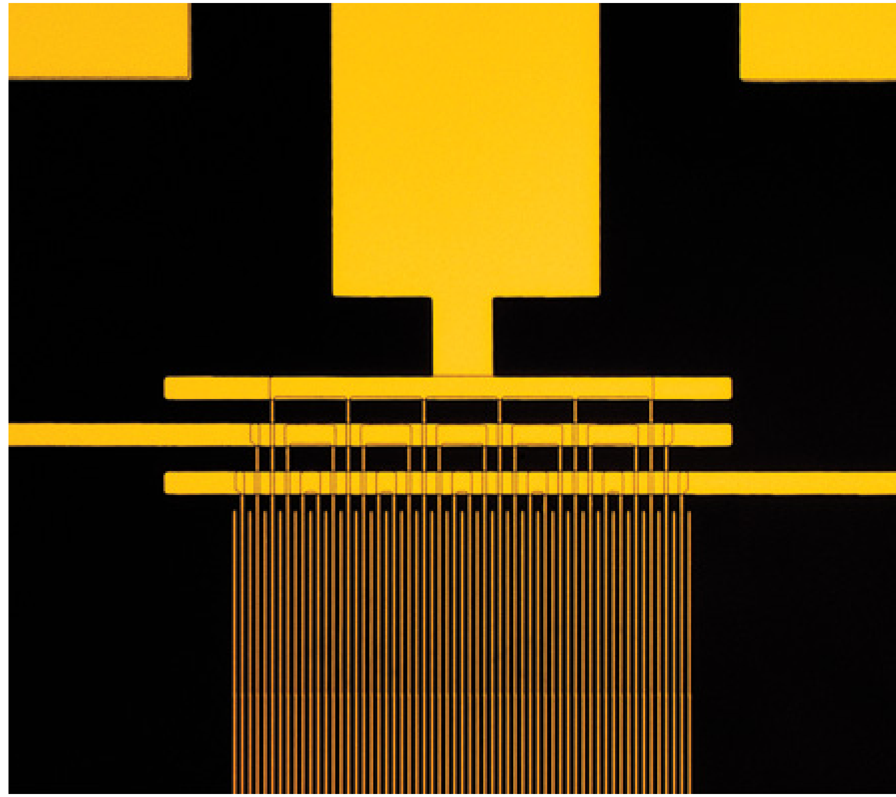
While we all love looking at the wonders of the night sky, and marvel at the images from the Hubble Space Telescope, much of the important work in astronomy is done at non-visible wavelengths. To better understand the universe, scientists rely on many different kinds of instruments to view deep space objects in the X-ray, ultraviolet, infrared, and other frequency ranges. These instruments often use diffraction gratings—generally some form of etched silica—to better interpret what lies beyond.

These devices come with limitations, however. Modern designs tend to be restricted to specific bandwidths. They are also size-constrained when flown on spacecraft, limiting what bandwidths they are capable of observing—one device, one set of frequencies per diffraction grating. Devices with multiple gratings often require power-hungry switching mechanisms to change their observational ranges. These and other limitations can limit how much scientific work a specific spacecraft can do, and can result in highly specialized (and expensive) missions.

JPL technologists have developed a first-of-a-kind device, called a Tunable Surface Acoustic Wave (SAW) Diffraction Grating, that uses acoustic resonance in a physical material to allow one diffraction grating to make measurements across a range of frequencies. In the same way that a stringed instrument like a violin is tunable to play a wide variety of notes, these gratings can be tuned to observe at different wavelengths. They are tuned electrically in a predictable and reliable fashion, eliminating the need for bulky, unreliable mechanical tuning.

The SAW diffraction grating system is more robust than mechanical ones, and therefore is more resistant to the violence of launch. It is simpler to manufacture and is more compact and less power-hungry than existing systems, and can be used across a much wider set of spectra. All these characteristics allow for increasingly ambitious observations of planetary surfaces, icy moons, and stellar objects across wide swathes of the electromagnetic spectrum—and more science for less money.

ADVANCES IN MATERIALS AND NANODEVICE FABRICATION ENABLE TUNABLE GRATINGS THAT SPLIT LIGHT BASED ON ACOUSTIC RESONANCE.



An optical image of a tunable surface acoustic wave transducers used for tunable-pitch diffraction gratings.

CLEAN SWEEP

ROBUST MARTIAN AND LUNAR DUST REMOVAL TECHNOLOGY ENABLES SURFACE OPERATIONS

The dust removal tool mounted on the Perseverance rover on Mars.

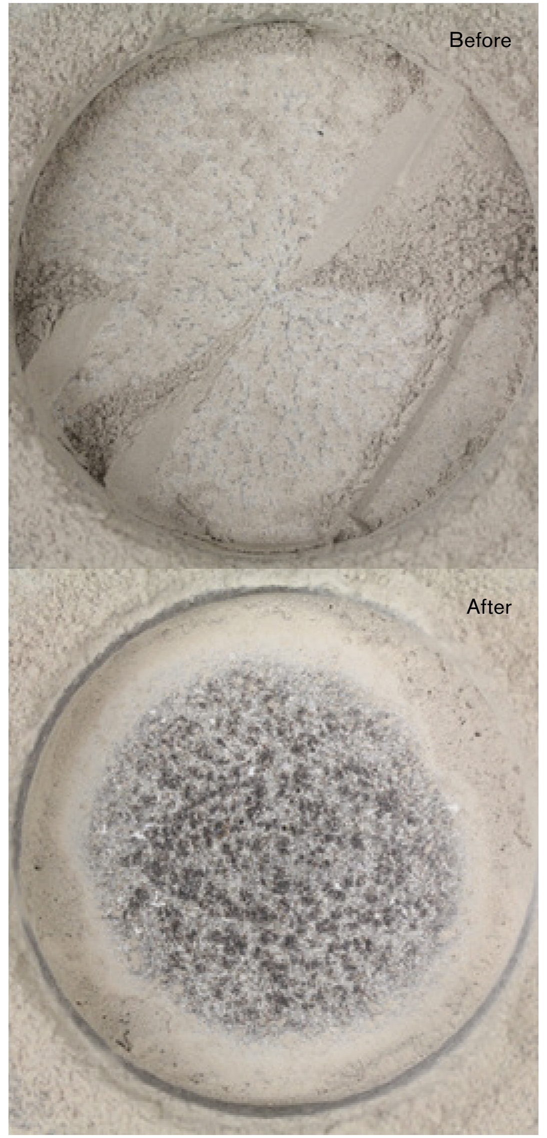
Dust is a constant challenge for lunar and planetary surface missions. Whether it's getting caught in instruments, clogging wheels, interfering with cameras and solar panels, or obscuring a potential sample, it can compromise even the most advanced mission. Dust is abrasive and potentially damaging to both moving and stationary components. Existing dust removal technology using brushes requires the presence of an atmosphere, while other techniques may not be capable of surviving extreme temperatures, like the lunar night.

LONG-TERM PLANETARY SURFACE ACTIVITIES REQUIRE ADVANCES IN DUST REMOVAL TECHNIQUES.

JPL Technologists have developed a compressed gas dust cleaning system that is mounted on the Perseverance rover manipulator now operating on Mars. It is a compressed gas system, which carries ultra clean nitrogen gas loaded on Earth, that is used to clear dust from abraded samples. The samples can then be imaged and analyzed by the Perseverance PIXL and SHERLOC instruments. The gas flow is supersonic, and is designed to have sufficient momentum and energy to remove dust from abraded surfaces about 1.5 to 2 inches (4-5 centimeters) in diameter and about a half-inch (1.6 cm) deep while withstanding the Martian environment without requiring survival heating for operation.

Success on Mars has opened the door to using similar capabilities on the Moon. The lunar version of this system, currently in development, is a self-contained and scalable tool that removes surface dust using a variable-strength flow of purge gas. When needed, it will be fetched by an articulating arm and latched to the arm's universal tool holder. Dust removal, then, combines two next-generation technologies: a modular and refillable lunar dust removal tool called LDRT that is optimized for operation on the lunar surface, and a 4 degree-of-freedom six-foot (2-meter) robotic arm, called COLDArm, that will fetch and mechanically position the tool.

The lunar system will need to be even more tolerant to cold temperatures than the Martian design in order to survive the lunar night, which can plunge to minus 298 degrees Fahrenheit (minus 183 Celsius). It will also be used on a wider range of surfaces, extending the life of at-risk and sensitive equipment such as articulating mechanisms, lenses, sensors, and solar arrays. The system also mitigates the risk of electrostatic discharge due to uneven surface dust accumulation, a severe risk on the Moon. These new capabilities will allow for a more sustainable robotic and human presence on the moon and Mars, both of critical importance to eventual long-term habitation by future human explorers.



Dust removal test results, before (top) and after (bottom) being cleaned with high-pressure gas.

LASER FOCUSED

HIGH-RESOLUTION LASER IMAGING FOR AUTONOMOUS HIGH-RISK LANDINGS

Artist's impression of performing high precision landing in rugged and challenging surface of an icy moon in the outer solar system.

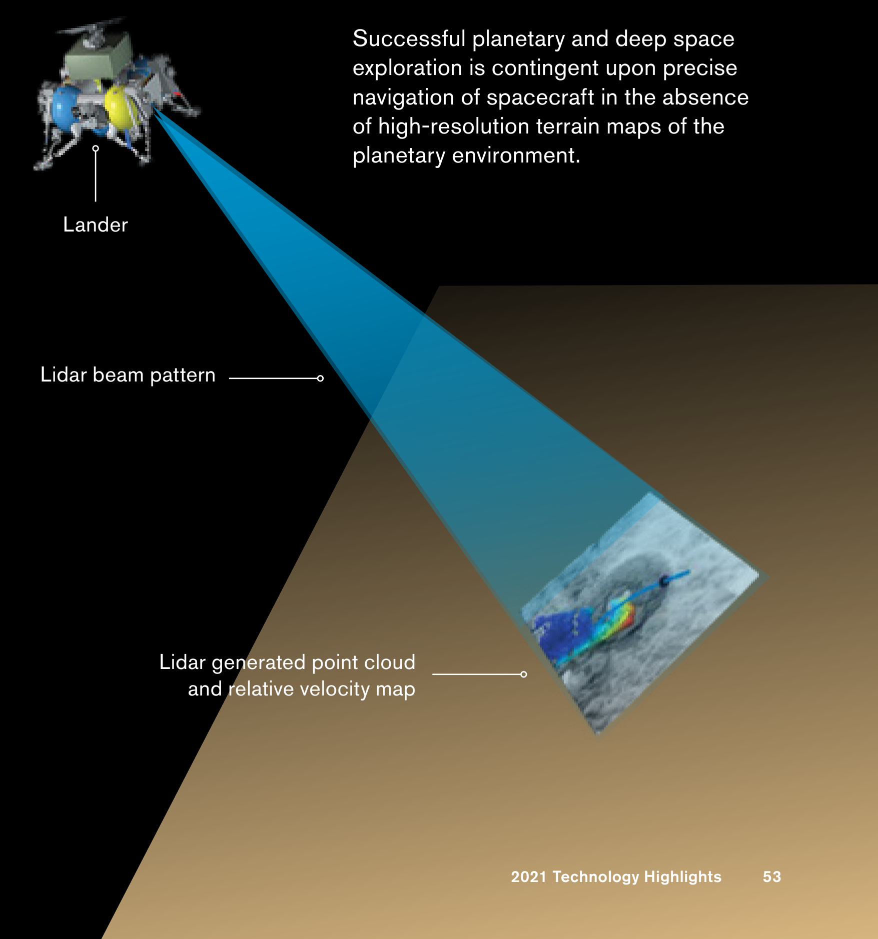
The world held its breath as the Perseverance rover landed on Mars. It successfully endured the "seven minutes of terror," having plunged directly through the Martian atmosphere after a 300-million-mile (482-million-kilometer) journey from Earth. This was the most recent of a string of successful NASA rover landings on Mars; other planned targets, such as Venus and the ocean moons of the outer solar system, will be even tougher. These landings will be an intricate ballet of careful guidance and trajectory calculation on-the-fly, all performed without the intervention of terrestrial mission control—instructions can take hours to arrive at extreme distances, so these machines are on their own.

While Mars has been thoroughly mapped from orbit, and Venus is not far behind, other targets, like Jupiter's moon Europa and Saturn's moon Enceladus, have only been glimpsed by flyby missions—we still do not know much about their surface topography. These are places of mystery, with rugged, forbidding terrain that is largely uncharted. To land safely, developing lightweight technology that includes real-time hazard detection and avoidance is essential.

To accomplish this, JPL and partners are evaluating a Frequency Modulated Continuous Wave (FMCW) Light Detection and Ranging (LIDAR) system that uses multiple laser beams to make high-rate data position measurements of the clouds of points created as the laser beams strike surfaces in the field of view. Each of the beams can measure more than 2 million points per second at distances beyond about 1000 feet (300 meters). Unlike traditional lidars, they can directly measure the position and radial velocity of the sensor relative to the terrain—without the use of an inertial sensor. The result is a safe, efficient trajectory to a successful landing performed completely autonomously by the spacecraft. The lidar system is more accurate and eliminates the need for radar, reducing spacecraft mass, complexity, and power requirements.

COMPACT, MULTI-BEAM LIDAR TECHNOLOGY ENABLES AUTONOMOUS LANDINGS IN UNKNOWN TERRAINS.

The result of this work will be more precise landings using more compact guidance systems—opening the trade space for additional payload mass and enabling greater science return. With such systems, difficult landings on distant targets of high-priority scientific interest become possible, potentially unlocking answers to critical questions in planetary science.



Successful planetary and deep space exploration is contingent upon precise navigation of spacecraft in the absence of high-resolution terrain maps of the planetary environment.

Counter-rotating rasps cut through surface material throwing sample material into a guide that directs it into a sealable sample collection cup.

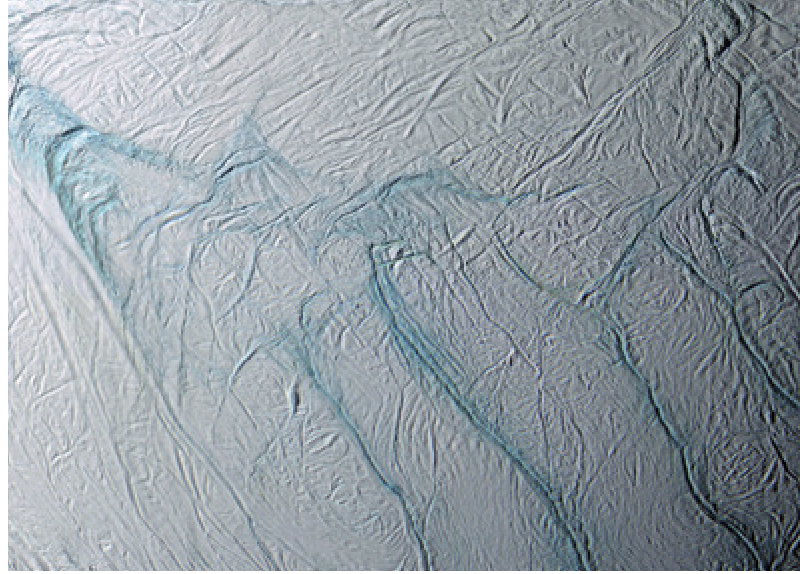
A SAMPLING SYSTEM FOR LOW-GRAVITY ENVIRONMENTS

SCRATCHING THE SURFACE

Collecting samples on distant worlds is extremely difficult and the robots we send into space must be uniquely qualified to perform this task. The challenges are vast. Some samples must be scooped, others scraped, and still others will need to be dug out of awkwardly located sites, difficult to reach with existing technologies.

THE SAMPLING OF PLUME DEPOSITS ON ENCELADUS COULD INDICATE LIFE.

JPL's new Dual-Rasp sampling and sample transfer system has been developed for missions requiring shallow surface samples and is particularly well suited for the unique conditions found on Saturn's moon Enceladus, a prime target for future exploration. The system can operate in a hard vacuum and in extremely low temperatures, and is capable of sampling in low gravity environments.



The surface of Saturn's icy moon Enceladus presents unique sampling challenges that may be addressed by JPL's Dual Rasp sampling system.

The Dual-Rasp sampling system being tested during a zero-g aircraft flight.

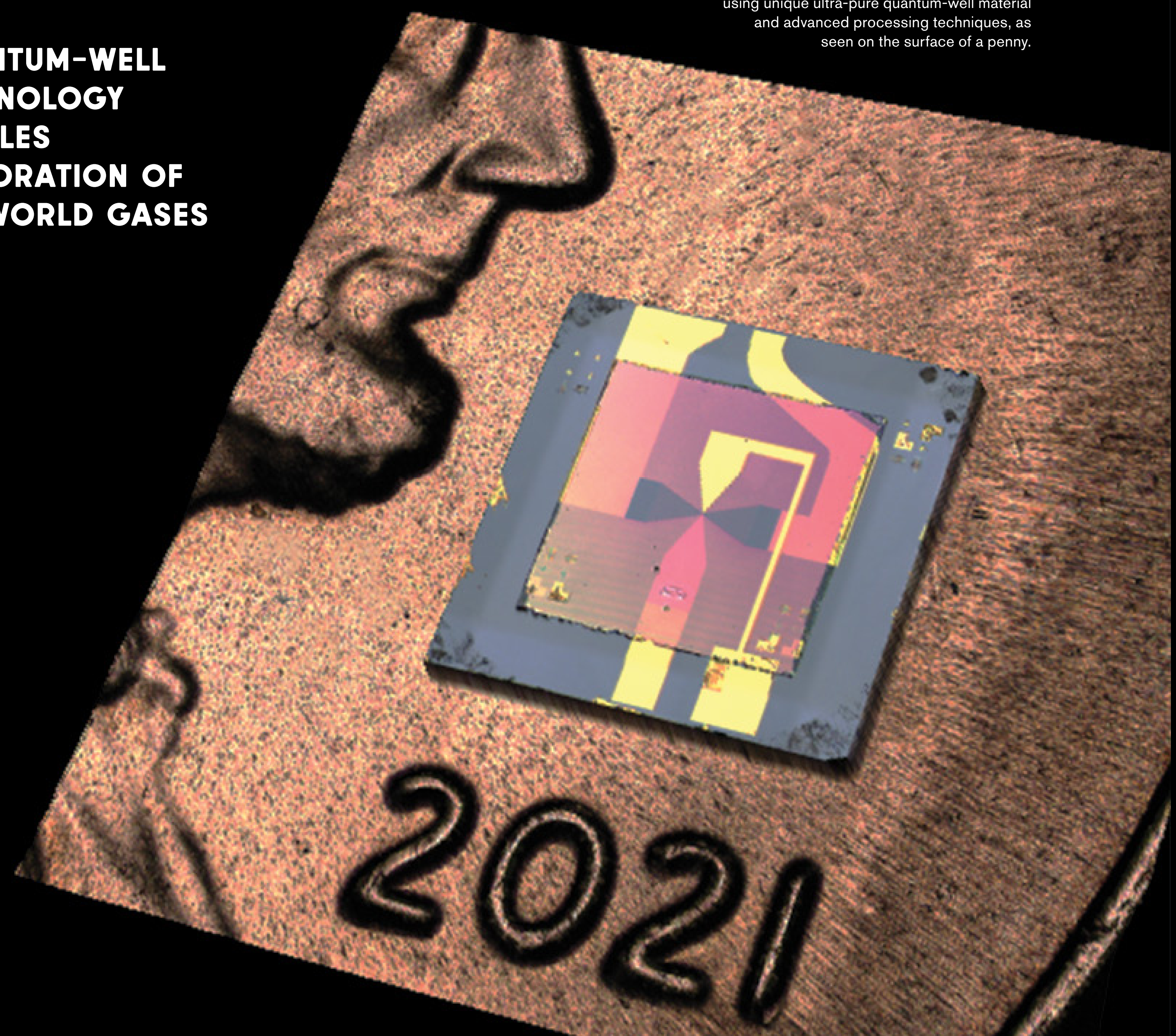
The twin counter-rotating rasps would cut through surface ice deposits, and the resulting sample is delivered to a collection cup, which uses grids to retain samples in low gravity conditions. The mechanism then closes to allow pressurized gas to transport the sample to instruments inside the lander.

The function of the Dual-Rasp sampling and sample transfer system's operation has been extensively modeled in software tests, and a mockup has been tested in a cold vacuum. Additional testing was performed in low-gravity conditions aboard a zero-g test aircraft. Target sample materials of differing consistencies and strengths were tested, and particle trajectories were tracked to assure collection of the samples. The system was also demonstrated in a thermal vacuum chamber to validate operation in Enceladus surface representative conditions with ice simulants of varying strengths. The ice simulants were produced using atomized water that was allowed to sinter to produce representative Enceladus surface material.

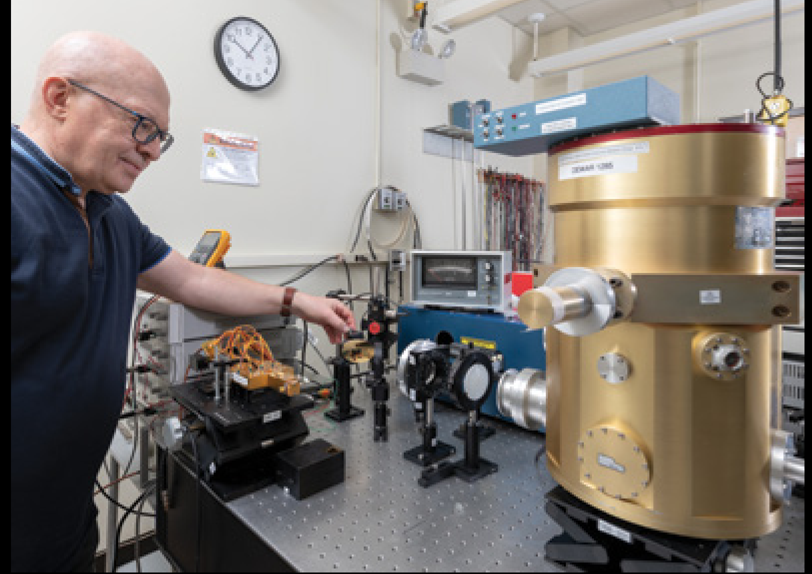
As we continue to explore the solar system, voyaging to ever more challenging environments, robust and accurate sampling technologies will be critical to success. The Dual-Rasp sampling and sample transfer system may be a critical enabling technology moving ahead—and may one day deliver the key sample that indicates life within a distant, frozen moon.

QUANTUM MIXING

QUANTUM-WELL TECHNOLOGY ENABLES EXPLORATION OF ICY WORLD GASES



The tiny TACIT detector chip, fabricated using unique ultra-pure quantum-well material and advanced processing techniques, as seen on the surface of a penny.



TACIT detector prototypes are tested at JPL using various radiation sources.

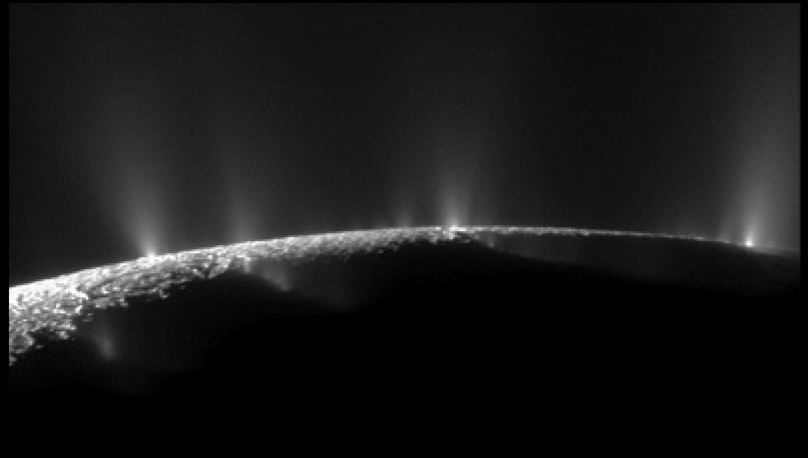
When Sherlock Holmes went about solving crimes, he did so by inference and deduction. Likewise, when exploring the reaches of the solar system, planetary scientists must often do the same—look at phenomena that are often only indirectly related to their questions and deduce the answers. One way to accomplish this is to study the extremely cold, often wispy atmospheres of the outer solar system's planets and moons to learn more about their composition and characteristics. This is best done in the terahertz (THz) frequency range, the emission zone of many atmospheric molecules. Sensing these molecules, though requires sensitive detectors.

A SEMICONDUCTOR, TUNABLE, TERAHERTZ SENSOR USES QUANTUM PHYSICS TO OPERATE WHERE PRIOR DEVICES COULD NOT.

The JPL-led MIRO instrument on the European Space Agency's Rosetta mission is the most capable heterodyne planetary instrument flown to date, but its spectral coverage was just a fraction of a THz, limiting its abilities. MIRO's detectors, based on Schottky diodes (a specialized fast-response semiconductor), made important, ground-breaking measurements, but were power-hungry and had sharply limited sensitivity.

JPL technologists, collaborating with the University of California at Santa Barbara (UCSB), are developing a new semiconductor detector—the Tunable Antenna-Coupled Intersubband Terahertz mixer (TACIT), which uses quantum wells, a cutting-edge technology, to constrain motion of the electrons emitted by incident radiation to two dimensions, rather than three, inside in the detector. This increases measurement accuracy and sensitivity. TACIT mixers are tunable, have low power requirements and minimal added noise, and operate above 60 degrees Kelvin (minus 351 Fahrenheit). The high operating temperature will make it possible to use passive radiative cooling rather than complex, power-hungry cryogenic coolers, and tunability allows adjusting the radiation absorption peak to frequencies corresponding to transitions in the quantum well, making autonomous deep space event-driven observations possible. TACIT detector prototypes have been constructed by UCSB and are currently being evaluated at JPL. In the future, a multipixel version of the mixer is planned to enable spectral imaging in the THz range, useful for both planetary science and astrophysics.

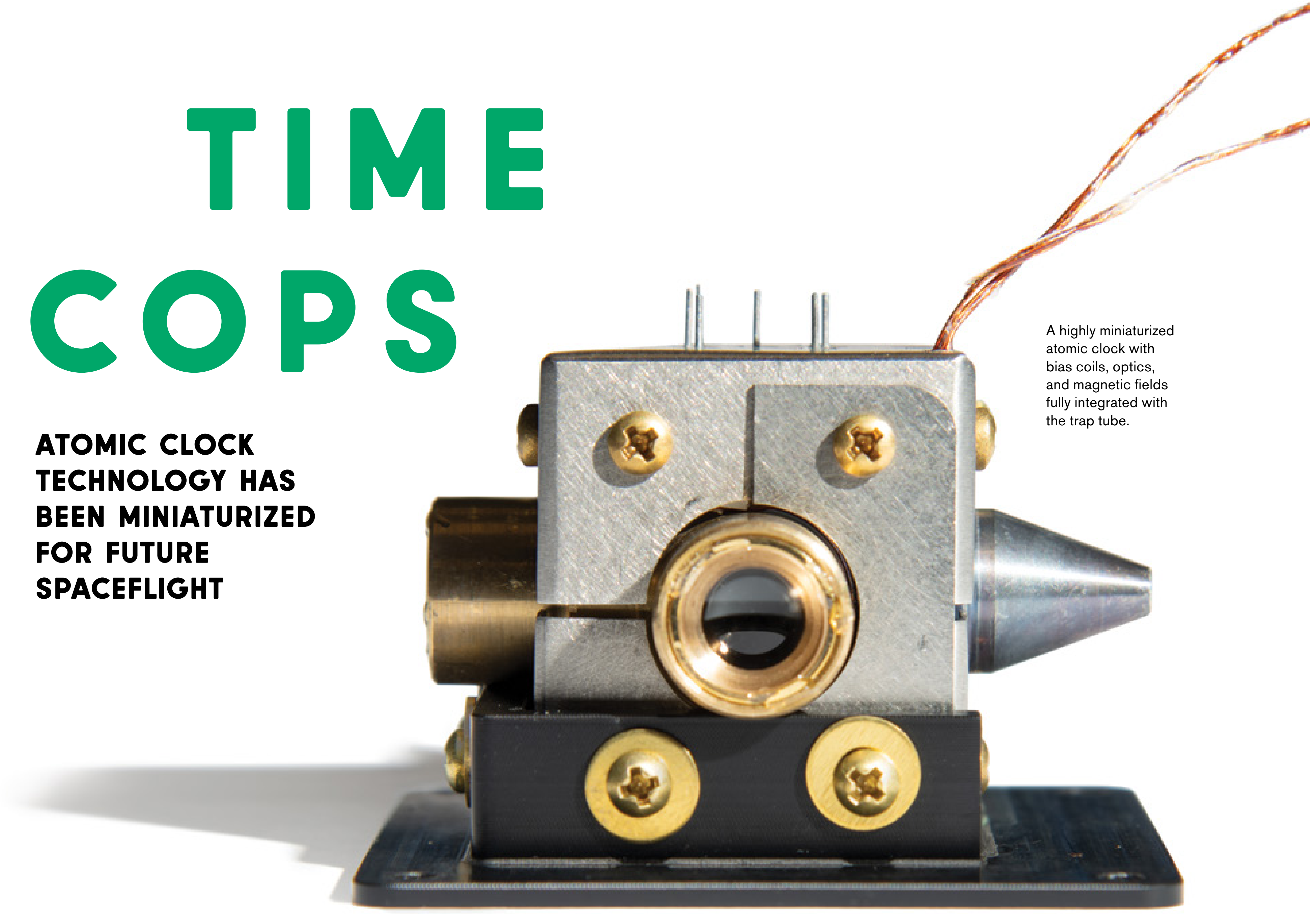
The TACIT mixer will be useful across a range of applications, in particular the investigation of the frigid giant planets Uranus and Neptune, as well as the icy oceanic moons, such as Enceladus, of the outer solar system.



Future THz instruments could study gaseous plume material ejected from Enceladus, one of Saturn's moons, providing information on its sub-surface ocean.

TIME COPS

ATOMIC CLOCK TECHNOLOGY HAS BEEN MINIATURIZED FOR FUTURE SPACEFLIGHT



A highly miniaturized atomic clock with bias coils, optics, and magnetic fields fully integrated with the trap tube.

Knowing the time has never been easier. Clocks all over the world reference extremely precise atomic clocks on Earth. Atomic clocks enable GPS navigation, among other capabilities, and in space they allow us to navigate distant reaches of the solar system with unprecedented precision.

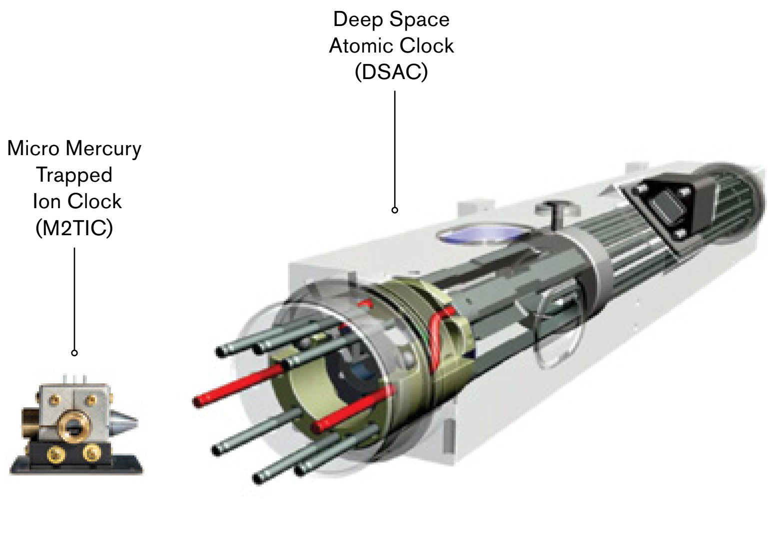
Accurate timekeeping is essential as we explore more deeply into space. The time it takes for a signal to get to and return from a spacecraft tells us how far away it is because the speed of light in space is constant. When many of these time measurements are combined, the direction and speed of a spacecraft can be calculated very precisely, permitting accurate navigation. This requires accuracies to within billionths of a second to know a spacecraft's position within about a yard (one meter) that, over time, could mean the difference between mission success or failure.

Today, we accomplish navigation one spacecraft at a time, since the Deep Space Network of antennas on Earth relies on two-way communication, and cannot talk to more than one spacecraft at a time—a major limitation when operating multiple spacecraft in deep space. To enhance our exploration of the solar system, a much more compact and power-frugal system is needed, one that can be carried onboard the spacecraft.

MICRO TECHNOLOGY ADVANCES PRODUCE A 10 CUBIC CENTIMETER MICRO MERCURY TRAPPED ION CLOCK FOR ACCURATE POSITION NAVIGATION AND TIMING ANYWHERE IN THE UNIVERSE.

Accurate atomic clocks on Earth can be as big as refrigerators, requiring too much space and power for spacecraft with limited resources. This solve this, JPL technologists led development of a Micro Mercury Trapped Ion Clock (M2TIC) that is 10 times smaller (only 10 cubic centimeters) and less power-hungry than its predecessor Deep Space Atomic Clock (DSAC). M2TIC is 1,000 times more accurate than its best commercially available counterpart—enabling precise real-time radio navigation in space.

Miniaturizing and making atomic clocks even more precise while using less power will allow even the smallest satellites and deep space probes to navigate autonomously in real-time with unprecedented precision, using new artificial intelligence systems. It also allows for longer tracking times, a benefit that increases with distance from Earth.



The clock trap package of the micro clock compared to that of the existing DSAC clock, a reduction of more than 10-fold in size.

CORRECTIVE OPTICS

METASURFACES OFFER STRIKING NEW OPTICAL FUNCTIONALITY

A metasurface device on an optical testbed. Wavefront errors induced by a deformable mirror are sensed by the device, and can be corrected.

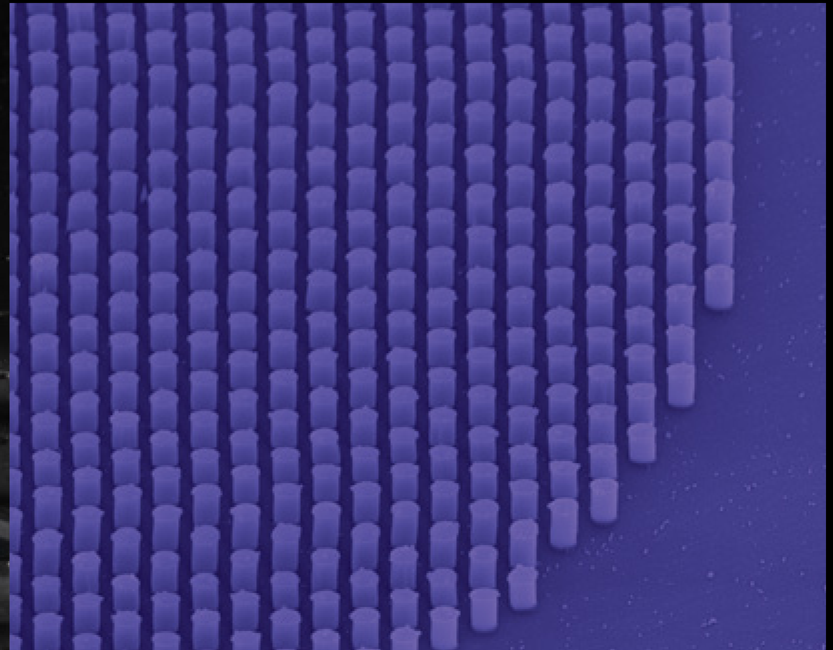
METASURFACES, AS OPPOSED TO TRADITIONAL OPTICAL ELEMENTS, CAN CONTROL MULTIPLE OPTICAL PARAMETERS SIMULTANEOUSLY ENABLING INNOVATIVE ASTRONOMICAL INSTRUMENT DESIGNS.

Anyone who's taken a deep dive into photography knows that crafting good optics is a tough slog. A camera lens that is tack-sharp is likely to skew colors a bit, and another lens that works well at low light levels will likely lack crispness. Creating near-perfect optics is almost a dark art, and no application is more demanding than deep space astronomy. The lenses and mirrors used in giant telescopes must be as close to perfect as we can make them, and their alignment is critical, especially when searching for distant, faint exoplanets. Until now, optics have typically had smooth shapes, made from metals and glass, to focus and correct the incoming light. Such optics, however, have limited ability to affect a light beam's optical parameters.

Metasurface optics, under development at JPL, aren't smooth. They have optical surfaces with extremely small, sub-wavelength, specially-shaped microfeature "posts"—arranged in calculated repeating patterns at a scale that is smaller than the arriving wavelengths of light they're designed to interact with. These surfaces modulate beam parameters depending on their shape, size, and relative orientation. Traditional optical elements, such as lenses and mirrors, typically only modify the phase of the incoming light, but using the detailed physics of light, metasurfaces can induce changes in phase, amplitude, and polarization simultaneously, significantly increasing the design space of optical elements while minimizing mass, volume, and complexity.

Direct imaging of exoplanets would benefit from real-time correction of optical errors in space-based telescopes by a process called wavefront sensing. In wavefront sensing, a metasurface device converts phase errors (e.g., wavefront errors due to optical misalignments in a telescope) into intensity variations that are sensed by a camera. We can use this information to correct a telescope's wavefront by repositioning and re-aiming mirrors or by using a real-time deformable mirror to cancel the errors.

JPL's Microdevices Laboratory is fabricating a metasurface wavefront sensor that is 30 microns in diameter, with several hundred 250 x 450 nm elliptical posts that are each 900 nm high. It will be tested at the W. M. Keck Observatory in Hawaii. Ultimately, this technology will allow us to see deeper into the universe than ever before, unlocking the secrets of its history, evolution, and future.



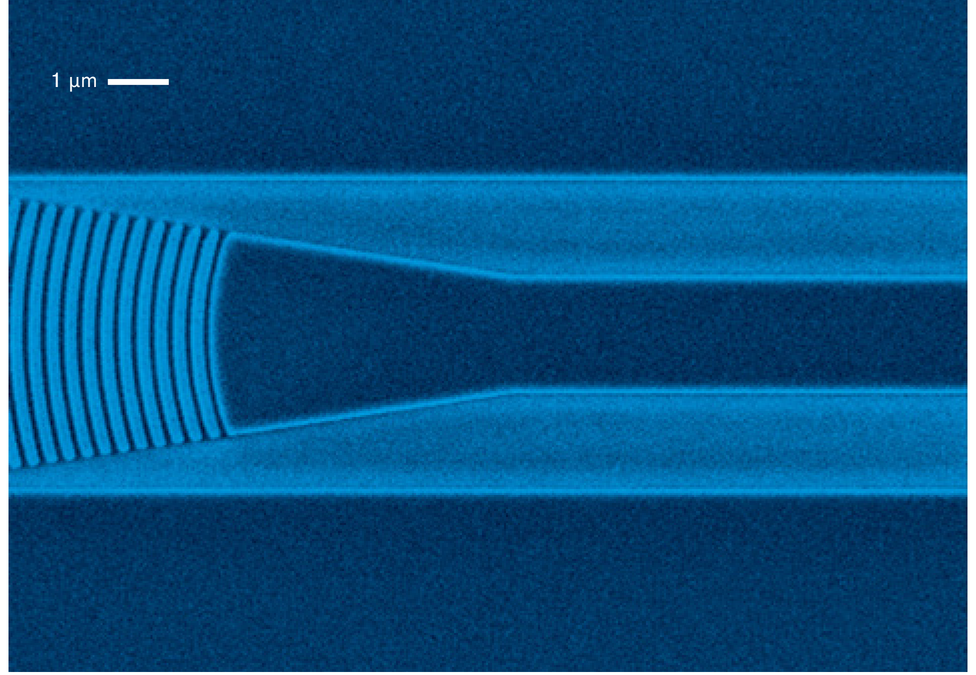
Left: Detailed view of a prototype metasurface device, fabricated in JPL's Microdevices Laboratory. Each pillar is 200 times smaller in diameter compared to a human hair.

Right: JPL Postdoc holding a silicon wafer containing a metasurface.

A prototype deep-ultraviolet laser on a microchip.

INTO THE DEEP

MINIATURIZED LASER TECHNOLOGY ENABLES THE SEARCH FOR LIFE



Grating coupler patterned in beta barium borate (β-BBO) using focused-ion-beam milling, featuring a period Λ=300 nm and designed for operation at a wavelength of λ=460 nm.

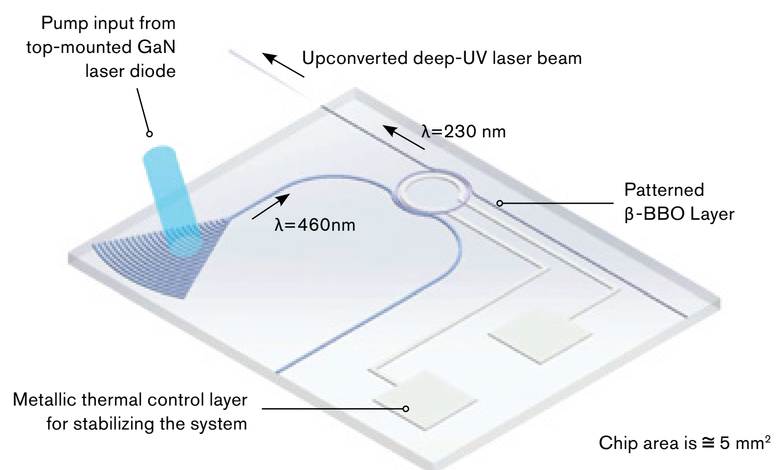
The sun showers us with ultraviolet light (UV) all day long, but in science, not all UV is created equal. Instruments that use Raman spectroscopy (a special type of spectral measurement that can determine the vibrational modes of individual molecules), or that measure a sample's laser-induced fluorescence spectra, require what is known as deep ultraviolet light—think of it as UV on steroids.

The generation of deep UV for this kind of science has traditionally been achieved by using gas lasers, but they are bulky and fragile, and not well suited to the harsh environment of spaceflight. A new chip-scale solid-state deep UV laser is being developed at JPL that will be well suited to operation on other worlds. It's about 100 times smaller than conventional UV lasers, and up to ten times more powerful, cutting down launch mass while being more efficient. The solid-state emitter also has improved beam quality in continuous-wave operation, and lasts longer than comparable gas lasers.

The key to this new technology is integrated photonic components (non-linear waveguides) that enable frequency conversion into the deep-UV from a solid-state blue diode pump laser. This approach allows flexibility in specifying the spectral characteristics of the deep-UV source based on the waveguide design—a capability not possible with traditional gas-based lasers. To achieve this within a chip-scale solid state device fabrication is performed within a low-loss ß-barium borate crystal, a notoriously challenging material to work with. JPL, however, has developed a new fabrication process, at the sub-micron scale, for lithographic patterning of ß-barium borate that enables fabrication of visible and UV-range photonic components within this material. This is a key technology advance that enables the development of compact coherent deep-UV light sources for in-situ instruments, allowing the non-destructive compositional analysis of organics, biosignatures, and other chemical species.

A COMPACT SOLID-STATE DEEP-UV LASER SOURCE FOR LIFE DETECTION AND CHEMICAL ANALYSIS ON MARS AND OCEAN WORLDS.

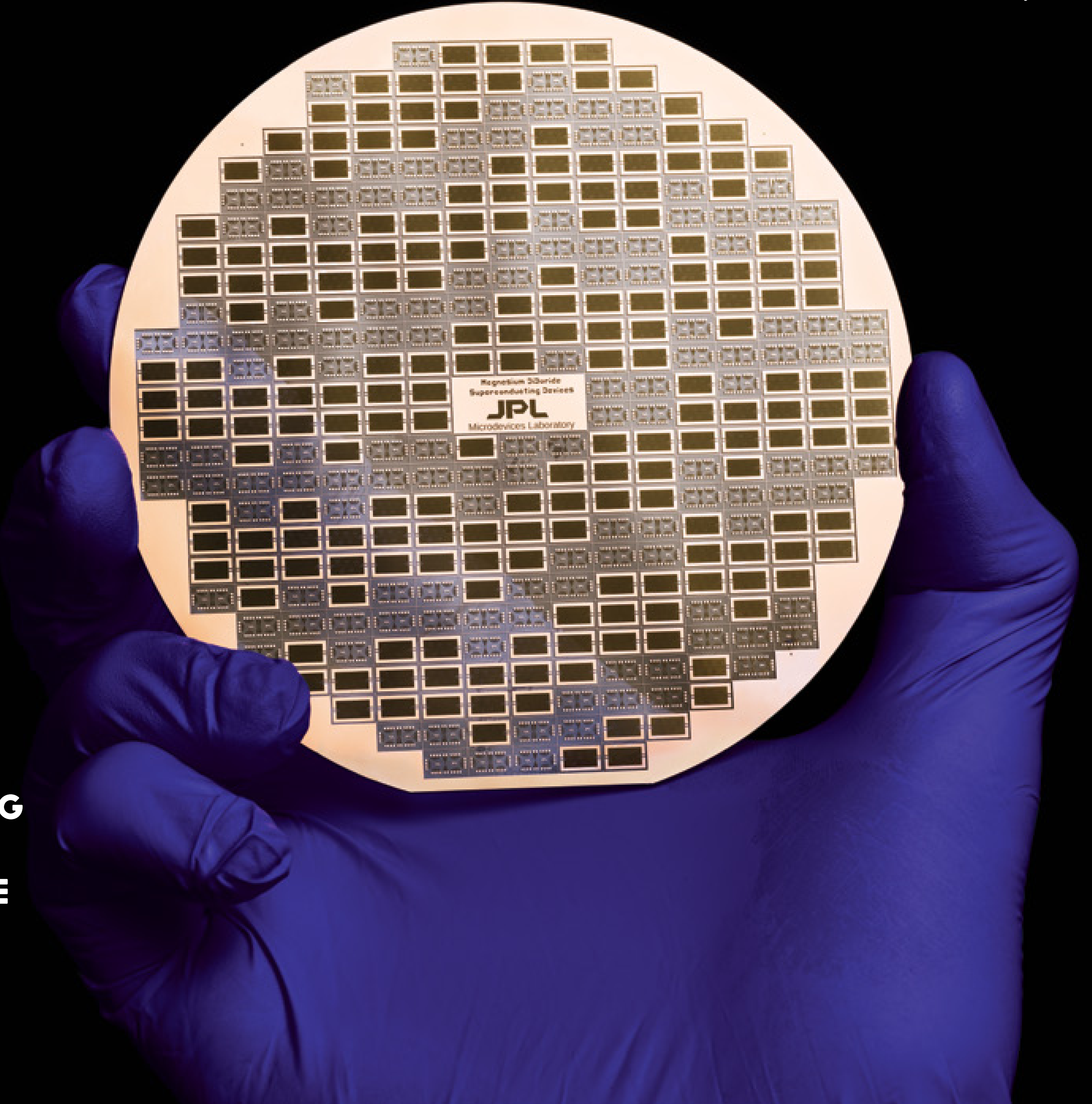
The deep UV laser will be useful across a wide variety of space exploration missions, including the ultra-accurate analysis of samples on Mars and the icy moons of the outer solar system—both prime targets of the search for extraterrestrial life. Accurate, non-destructive investigation of samples will be an enormous leap forward in this search, and for planetary science in general.



Schematic illustration of the beta barium borate (β-BBO) integrated photonic chip platform under development.

SENSITIVE SIDE

NEW SUPERCONDUCTING DEVICES PROMISE TO REVOLUTIONIZE ASTRONOMY



A JPL-fabricated superconducting-wafter sensing device that operates at higher temperatures than similar devices made today.

Like most modern systems, the advanced capabilities of space probes are enabled by semiconductor devices, and on a spacecraft, sensing is one of the their most critical applications. Normal semiconductor devices, however, are not suitable for detecting faint far-infrared light from the early universe, or photons from high data-rate deep space optical communication systems. For those applications we need the sensitivity and loss-free capabilities of superconducting detectors, in which electrical currents can flow without resistive losses.

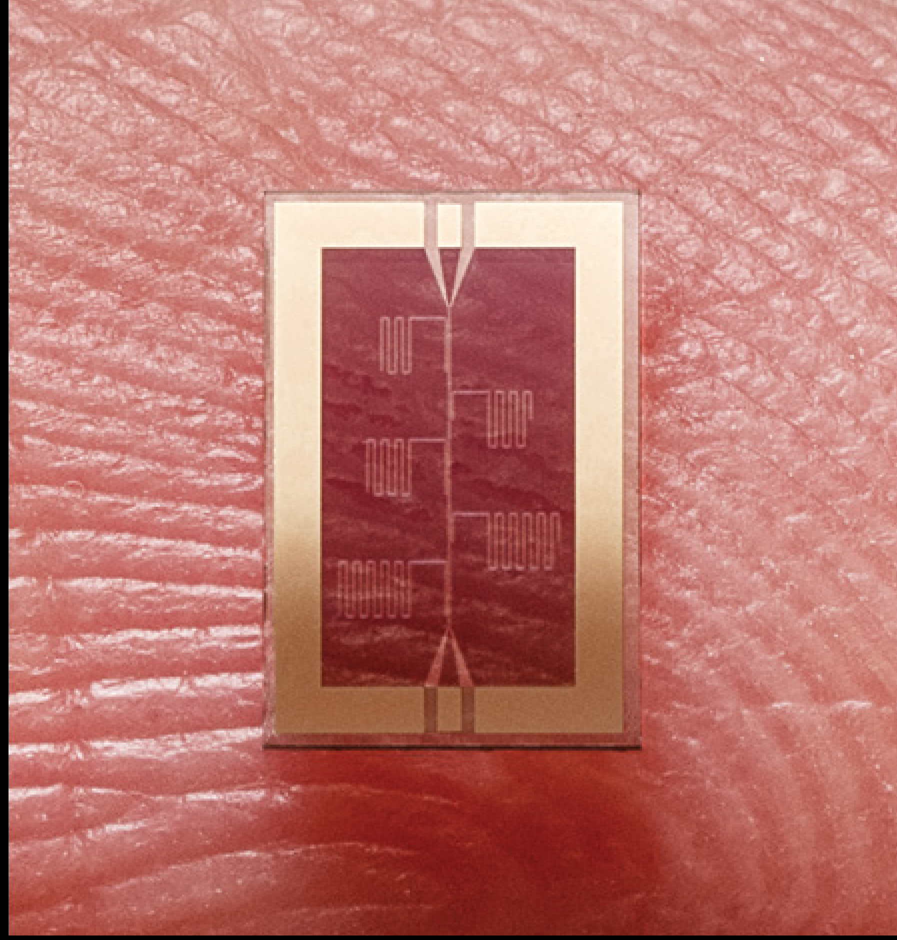
Superconductivity, though, is only possible at extremely low temperatures—below a material's "transition" temperature where it becomes superconducting. With typical state-of-the-art superconducting materials, these temperatures are difficult and costly to reach and maintain. Raising the transition temperature, then, is critical for realizing practical, affordable superconducting applications.

Using magnesium diboride (MgB_2), JPL engineers have fabricated new semiconductors that become superconducting at about minus 395 degrees Fahrenheit (or 64 degrees Fahrenheit above absolute zero), with an operating temperature of about 20 degrees Kelvin—warmer than traditional superconducting materials, which makes for smaller, easier to manufacture cryocoolers. MgB_2 also enables an increase in upper frequency limits beyond 1 THz, potentially enabling new mission types and instruments. A major goal of this research is to create mission-enabling, drop-in replacement materials to make new devices, including large remote sensing arrays.

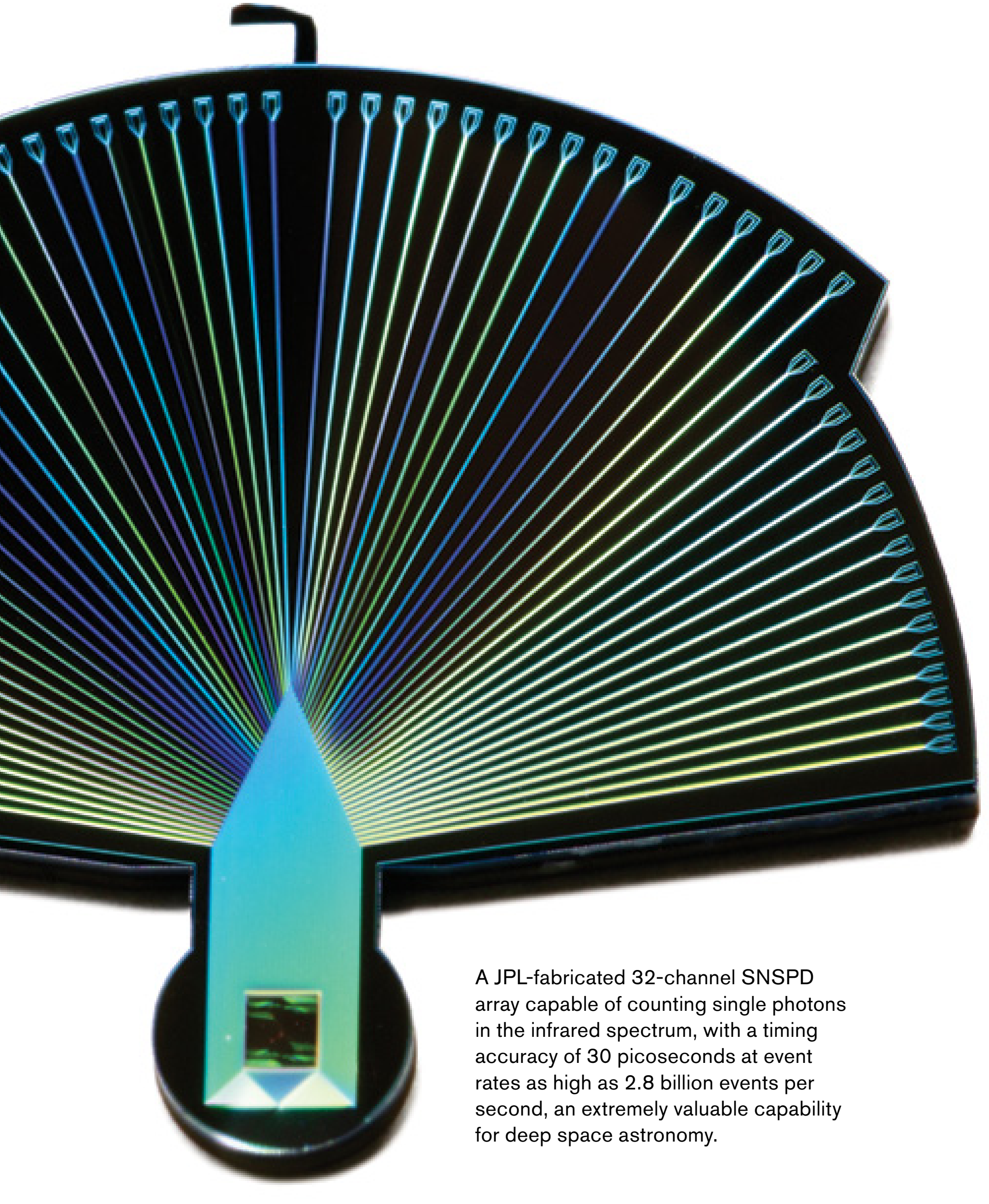
NEW MATERIALS AND SEMICONDUCTOR DEVICES TO MEET CRITICAL SCIENCE AND TECHNOLOGY NEEDS.

But there's a snag—magnesium diboride is hard to manufacture and challenging to scale up to useable sizes for larger instruments. JPL's new technology employs a scalable thin-film deposition process, using traditional microfabrication tools, to create very smooth surfaces (less than two nanometers in roughness) that can be fabricated quickly—the film annealing time is less than a minute. Adjusting the film chemistry tunes its resistivity, changing it by an order of magnitude with only a slight change in the superconductivity transition temperature. The resulting sensors are not just more sensitive at higher temperatures, they also have far more infrared sensitivity than their predecessors.

Due to the red-shift of light from very distant sources the most useful observations of galaxies, the interstellar medium, and the universe at large are performed in the infrared, where objects lie at extreme distances that tickle the edge of time.



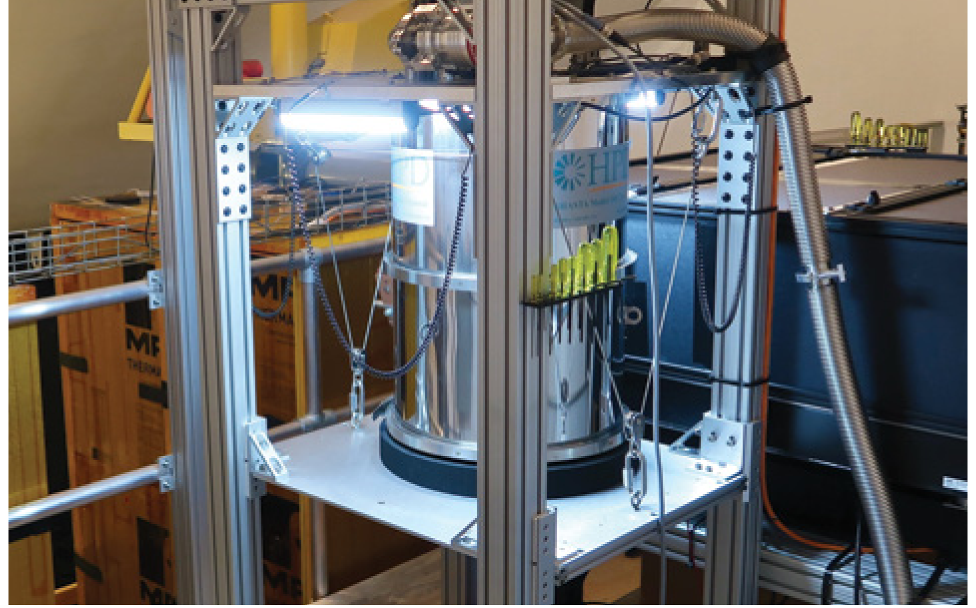
Close-up view of device used to measure and optimize microwave signal losses in the novel material system. The nearlytransparent superconducting film is 25 nanometers thick. The gold perimeter is used to make good thermal and electrical contact to the device.



A JPL-fabricated 32-channel SNSPD array capable of counting single photons in the infrared spectrum, with a timing accuracy of 30 picoseconds at event rates as high as 2.8 billion events per second, an extremely valuable capability for deep space astronomy.

EVERY PHOTON COUNTS

SUPERCONDUCTING NANOWIRE SINGLE PHOTON DETECTORS ACHIEVE WORLD-LEADING PERFORMANCE



An SNSPD installed at Caltech's Mount Palomar Hale 200-inch telescope as part of the Ground Laser Receiver for the Deep Space Optical Communications (DSOC) project.

In astronomy, sometimes simply capturing an image of a distant object is not enough—detailed measurements, including the energy and intensity of the arriving light, must be made to gain an understanding about the history and evolution of the universe. To achieve this, astronomers use sensors that capture the slightest bits of light—down to individual photons—to gain important insights. The ability to count individual photons is greatly beneficial, both scientifically and technologically, but achieving that ability has been very challenging.

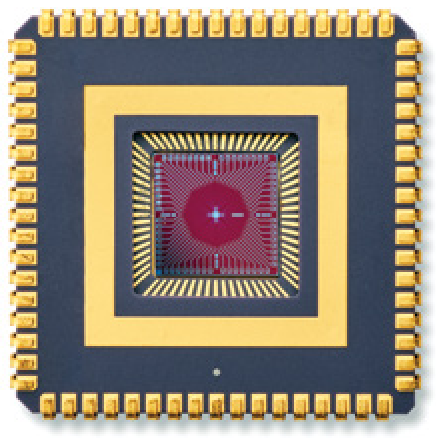
JPL engineers have achieved groundbreaking results with devices called Superconducting Nanowire Single Photon Detectors, or SNSPDs, which are currently the leaders in photon counting. Using superconductivity to increase sensitivity, efficiency, and reduce background noise, SNSPDs allow the tracking of single photons striking the detector one-by-one and, in a spectrometer, to measure their energy.

EXTREMELY SENSITIVE PHOTON COUNTING DEVICES PROMISE ADVANCES IN MULTIPLE DISCIPLINES.

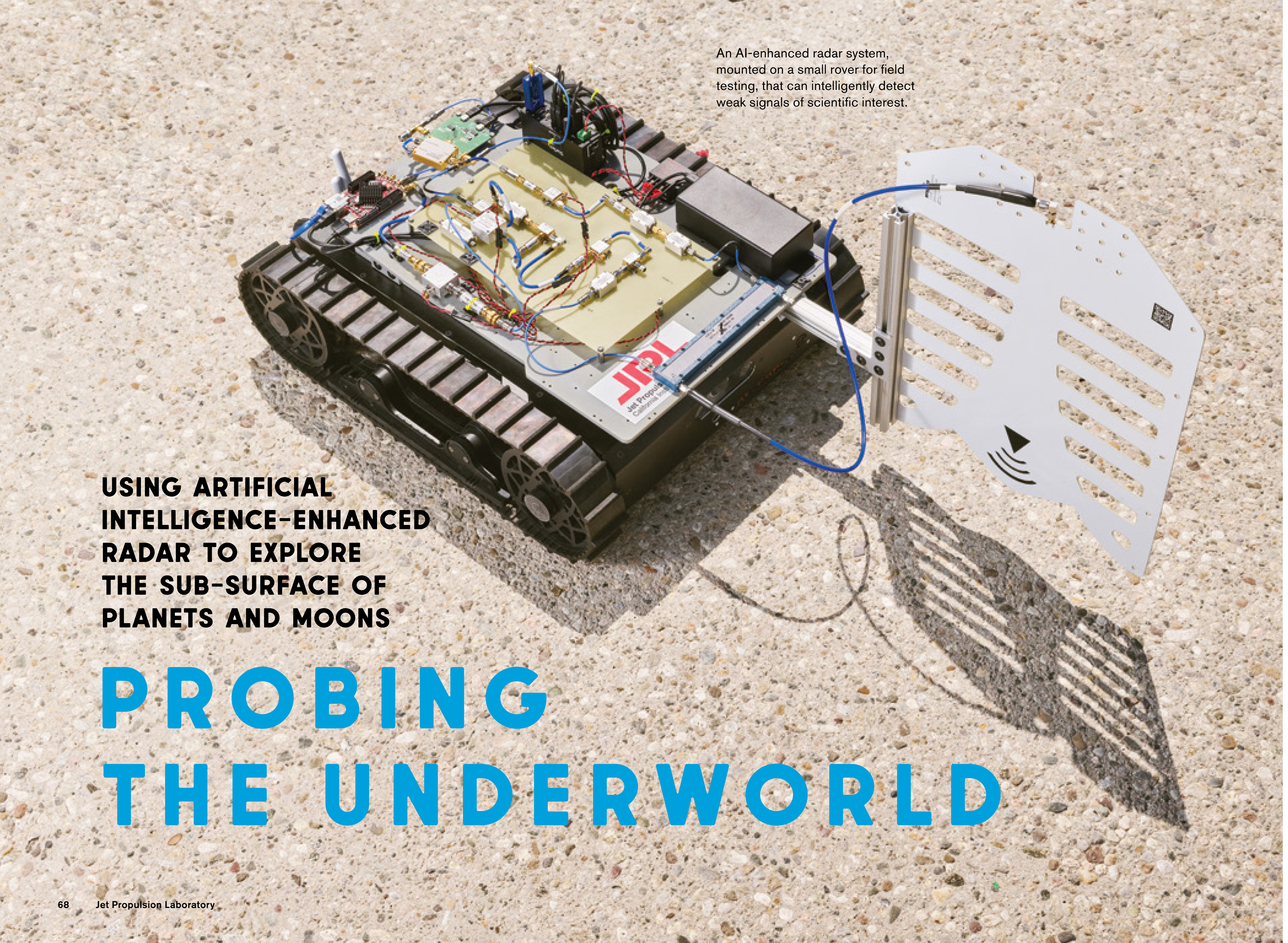
These sensors have uses well beyond astronomy. Earth-based SNSPDs will achieve the first demonstrations of optical communication from beyond lunar distances as part of NASA's Deep Space Optical Communication (DSOC) project launching on the Psyche asteroid mission in 2022. DSOC will demonstrate optical communication at ranges as far as 2.7 astronomical units (224 million miles), about 1000 times farther than the existing state of the art. This important experiment will achieve data rates as high as 267 Mbps, a huge advance in deep space communication. JPL-developed SNSPDs are also enabling optical communication in human spaceflight applications, through NASA's Optical-to-Orion (O2O) project, and will form the backbone of a future optical Deep Space Network—creating a leap forward in the tracking, control, and data volume received from distant spacecraft.

SNSPDs have already been used in areas as varied as quantum information technology, dark matter detection, and remote sensing. JPL is currently exploring the use of SNSPDs in future quantum networks, both in space and on the ground, as well as in future focal plane arrays for mid-infrared astronomy and exoplanet transit spectroscopy.

Ultra-sensitive Superconducting Nanowire Single Photon Detectors are at the cutting edge of photon detection and promise to expand into even more areas of scientific investigation and technology application in the future.



64-element SNSPD focal plane array developed at JPL for the NASA DSOC project.



An AI-enhanced radar system, mounted on a small rover for field testing, that can intelligently detect weak signals of scientific interest.

USING ARTIFICIAL INTELLIGENCE-ENHANCED RADAR TO EXPLORE THE SUB-SURFACE OF PLANETS AND MOONS

PROBING THE UNDERWORLD

Radar is an incredibly valuable resource for the exploration of the surfaces and sub-surfaces of planets and moons. Notably, large amounts of water and water ice have been discovered on Mars by ground-penetrating radar (GPR). The same technology is used on Earth to map underground pipes for construction and maintenance, and archaeologists use GPR to search for ancient artifacts deep underground. But because human-created items have known shapes and structures and are materially quite different from the soil that surrounds them, there's a huge difference in understanding the types of signals bounced back from human and natural deposits. Ice and water deposits tend to blend-in and are harder to discriminate.

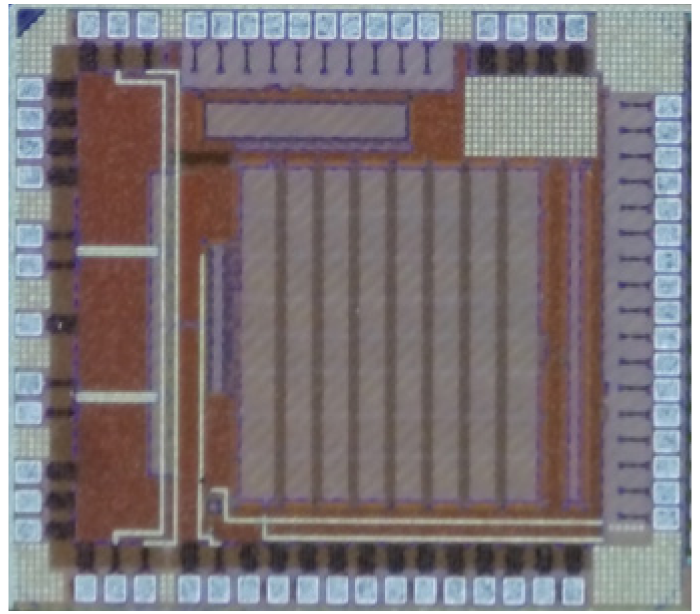
AI-DRIVEN RADAR CAN INTELLIGENTLY SELECT THE CRITICAL PARTS OF A SIGNAL AND REMOVE LESS IMPORTANT ONES, IMPROVING WEAK-SIGNAL SENSITIVITY AND OFFERING MORE COMPACT DOWNLOADS.

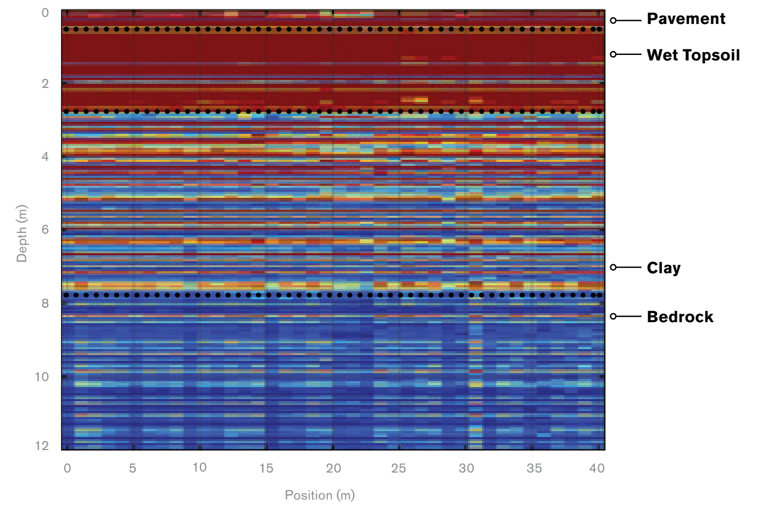
NASA is driven by both scientific and practical reasons to detect ice or water mixed beneath the soils of distant bodies. To detect and understand the layering that identifies underground features, and to help determine the story of how they evolved, radars must look for differences in soil moisture of only a few percent and find layers that are only millimeters thick. These features produce very weak radar signals that are difficult to detect—they can be overwhelmed by unwanted reflected signals from both the surface itself, and from extraneous signals that bounce around inside the radar, confusing interpretation. These signals can be more than 1,000 times stronger than the signals being sought.

To overcome this, JPL has developed a new radar technology that uses artificial intelligence (AI) software to look at all the signals received by the radar to determine which are echoes from inside the radar, as well as those reflected from the surface. The AI engine, much like noise-canceling headphones, then generates a counter signal that blocks the unwanted signals while leaving any weak sub-surface signals undisturbed so they can be detected and processed before being sent back to Earth. This will eliminate much of the time, downlink data volume, and even guesswork, in evaluating mission data.

Combining AI with radar will allow scientists to probe more precisely below the surfaces of planets and moons without needing to drill or excavate, and will be applicable to rovers, landers, and orbiters exploring the furthest reaches of the solar system.

A custom 28 nanometer processor chip containing the radar waveform generator, demodulator, and AI calibration engine technology needed for enhanced sub-surface exploration of environments such as planetary surfaces and icy moons.





Prototype ground-penetrating radar product measuring the sub-surface beneath a road at JPL.

DEEP INSIGHT

NEBULA SYSTEM ENABLES AUTONOMOUS EXPLORATION OF THE UNKNOWN

A Boston Dynamics robot fitted with JPL's NeBula sensor and computing package undergoing subterranean testing.

MODULAR AUTONOMY PACKAGE ALLOWS ROBOTS TO EXPLORE UNKNOWN ENVIRONMENTS WITHOUT HUMAN INVOLVEMENT.

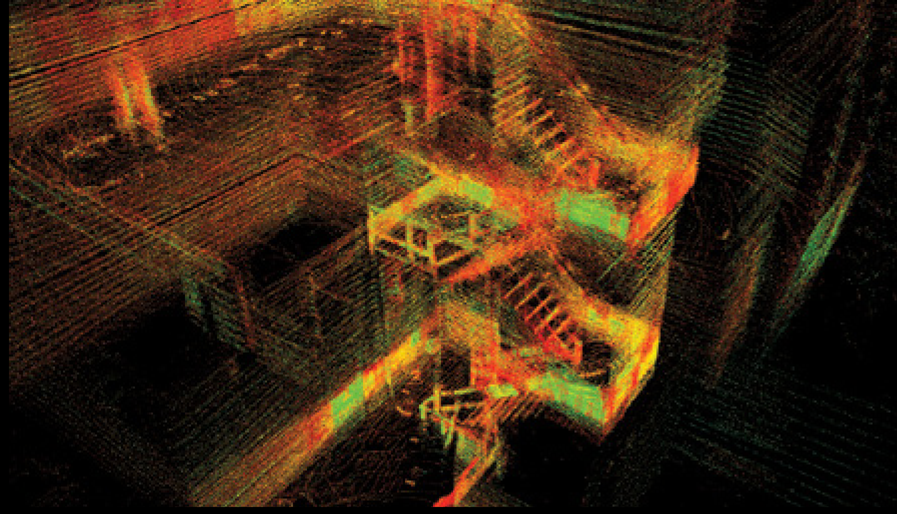
The search for life beyond Earth has begun in earnest. The Perseverance Mars rover is the first astrobiology mission since the Viking Mars landers of the 1970s and may identify life, or its precursors, in Martian soil. But the Earth is unique; harsh radiation and ultraviolet light conspire to sterilize the surfaces of most places beyond our planet, and it seems increasingly likely that life, should it exist off-Earth, may well be found underground where large rovers cannot tread.

Exploring caves and voids on other worlds is a challenging undertaking and a high degree of autonomy will be required of the robotic probes. By virtue of their ability to crawl beneath rocks or ice, these mobile explorers will be out of radio contact with Earth for extended periods of time. To address this, JPL engineers have developed unique, modular software called NeBula (Net-worked Belief-aware Perceptual Autonomy).

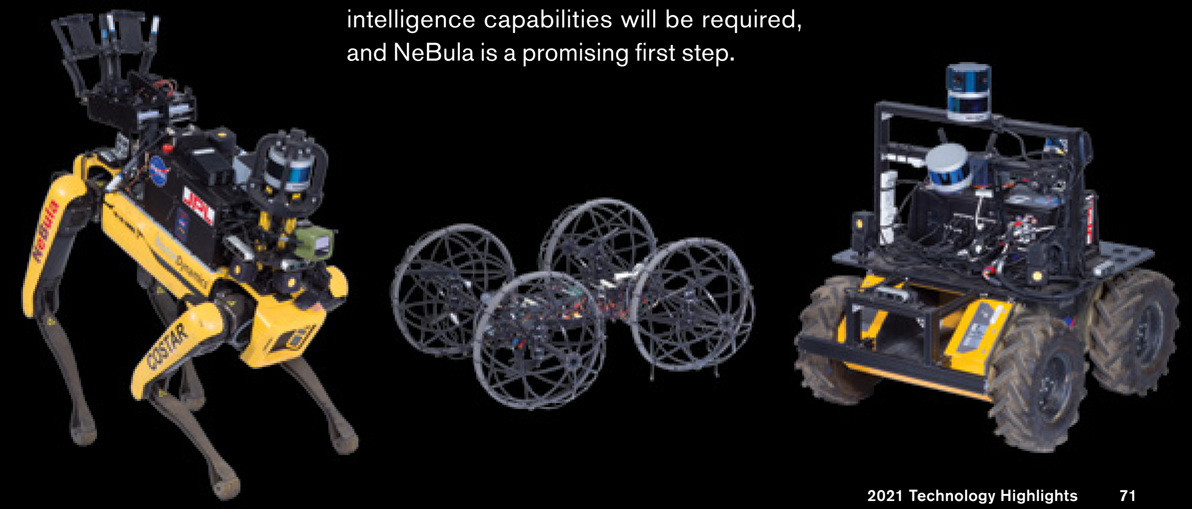
NeBula is specifically designed to identify and predict extreme, harsh, and unforgiving subterranean environments. To accomplish this, it uses a variety of metrics, including the motion of the probe, the nature of the environment it's exploring, onboard system health, and communication ability, creating a 3-D map along the way. NeBula is hardware-agnostic and can be used on a wide variety of mobile exploration technologies, including rovers with wheels, robotic legs, and tracks; as well as flying drones.

NeBula has been tested on a variety of prototype platforms and has performed with distinction, winning a recent DARPA Subterranean Challenge—one of the most difficult competitions of its kind in robotic autonomy. Test environments have included rugged lava tubes on Earth, where the software successfully navigated up to a third of a mile (one-half kilometer) of unknown (to the robot) subterranean terrain. This was the first time such and undertaking had succeeded at this scale.

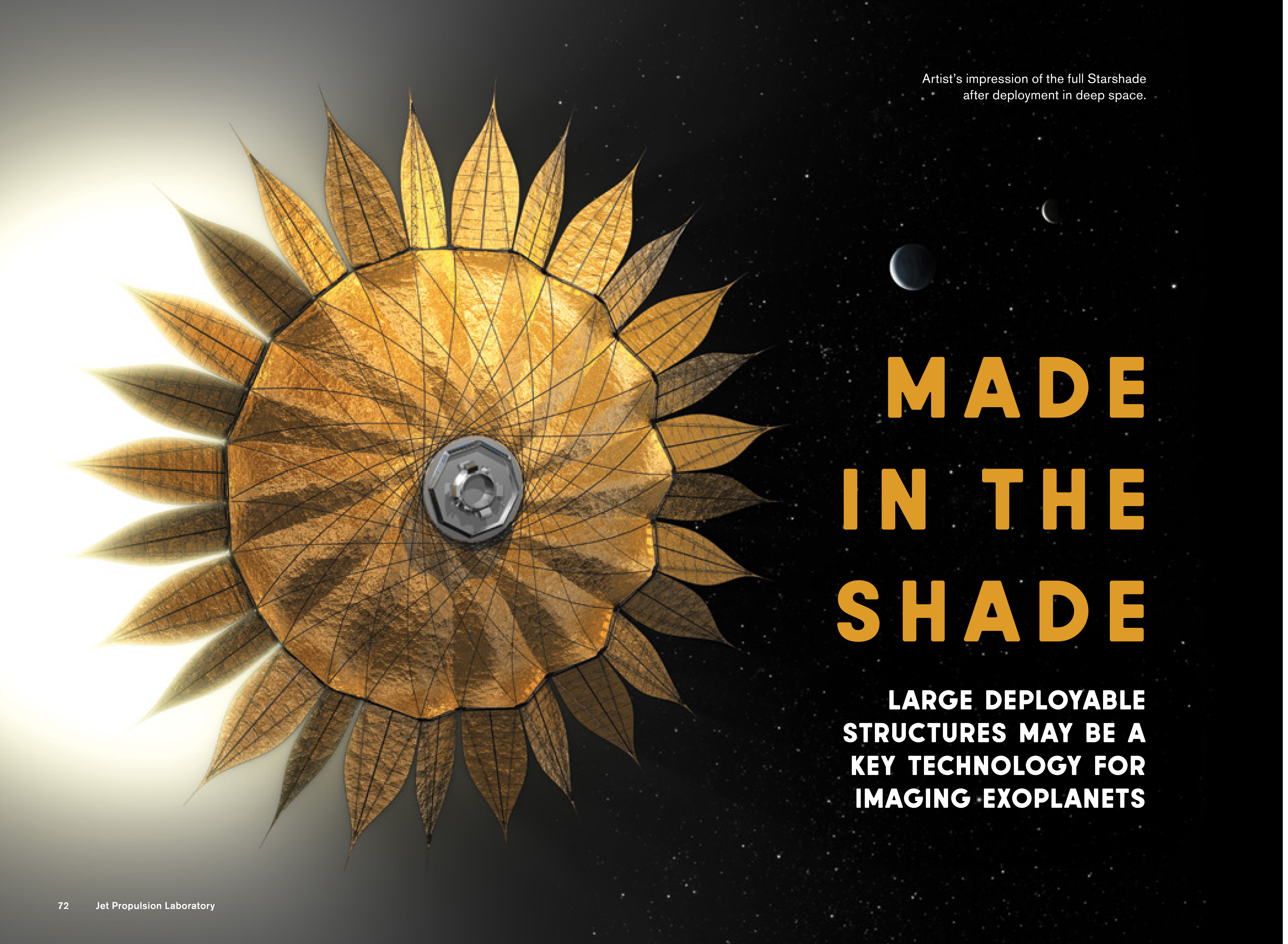
To explore the unseen features of planets and moons, seek life, and even identify potential habitation zones for human explorers, robots with advanced artificial intelligence capabilities will be required, and NeBula is a promising first step.



3D map generated by NeBula while traversing four flights of stairs. The map was created in real-time using onboard computation and software.



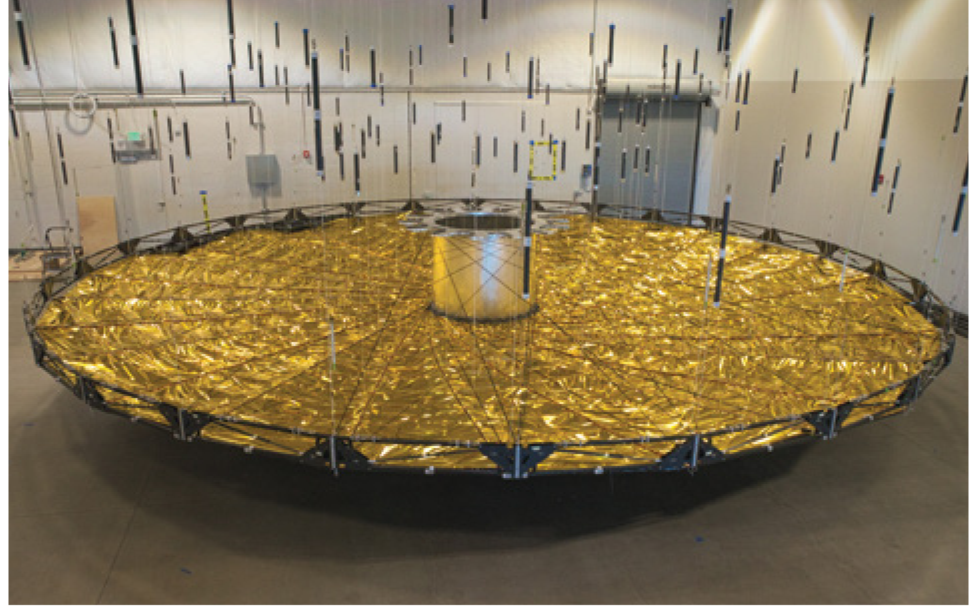
Team Collaborative SubTerranean Autonomous Resilient Robots (CoSTAR).



Artist's impression of the full Starshade after deployment in deep space.

MADE IN THE SHADE

LARGE DEPLOYABLE STRUCTURES MAY BE A KEY TECHNOLOGY FOR IMAGING EXOPLANETS



The Starshade Inner Disk System (IDS) prototype deployed in testing. The IDS is about 35 feet (10.6 meters) in diameter when deployed.

While few of the stars in our galaxy have been investigated for the presence of exoplanets, current findings indicate that, on average, stars have three orbiting planets where one in five Sun-like stars has an Earth-like planet in its habitable zone, the region where liquid water can exist.

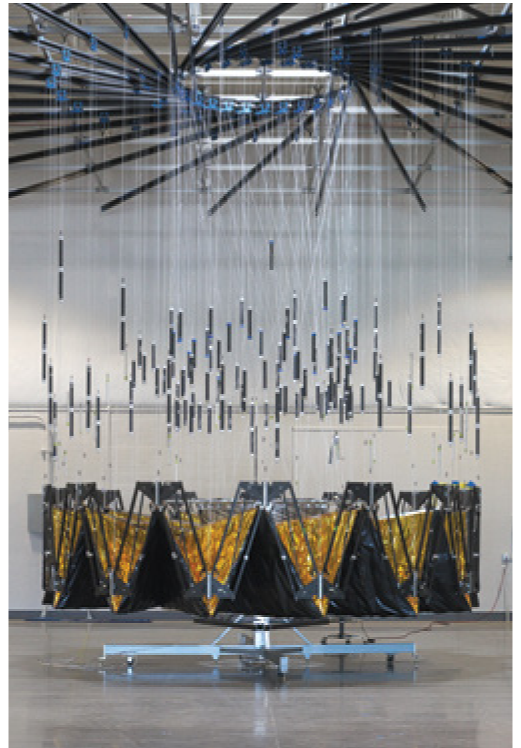
Detecting these planets, however, is hard. Stars can be up to ten billion times brighter than their orbiting planets, which become lost in the star's glare. To make exoplanets detectable, JPL and industry partners have developed a deployable 85-foot (26-meter) diameter flower-shaped starshade to block the glare, allowing the planet's faint light to be detected. The starshade will fly between the target star and up to 50,000 miles (80,000 kilometers) from the observing telescope, maintaining its lateral position perpendicular to the line of sight to within about a yard (one meter). While the starshade's petals block the target star's glare, the glint of the Sun's light reflected off the petal edges is still too bright. Fabricating the edges from ultra-thin sheets of metallic glass foil, processed to leave a sharp, one-micron radius edge, limits Sunlight glint while retaining sufficient flexibility for wrapping and deployment.

NEW CONTROL ALGORITHMS, MATERIALS, AND GEOMETRIC DESIGN ADVANCE STARSHADE TECHNOLOGY.

As the telescope observes target stars, the starshade must position itself accurately and maintain that position for up to several days to suppress the target star's light. This is difficult due to gravitational disturbances and solar radiation pressure, and requires new control algorithms and a sensing system that can measure the starshade's lateral position to within about a foot (a few tens of centimeters).

If the shape or position is off by more than the width of a few human hairs, light from the target star will leak into the telescope's field of view and overpower the planet's light. Development efforts have demonstrated that deployment is sufficiently accurate and that the petals will remain stable in shape and position despite disturbances caused by the space environment and target aiming maneuvers.

Starshade technology may enable future telescopes to capture the first visual images and spectra of Earth-like extrasolar planets, greatly improving our understanding of solar system evolution and possible pathways for the emergence of life.



The Starshade inner disk testbed unfolds at Tendeg in Louisville, Colorado. This testbed was used to demonstrate the deployment accuracy needed for Starshade concepts.

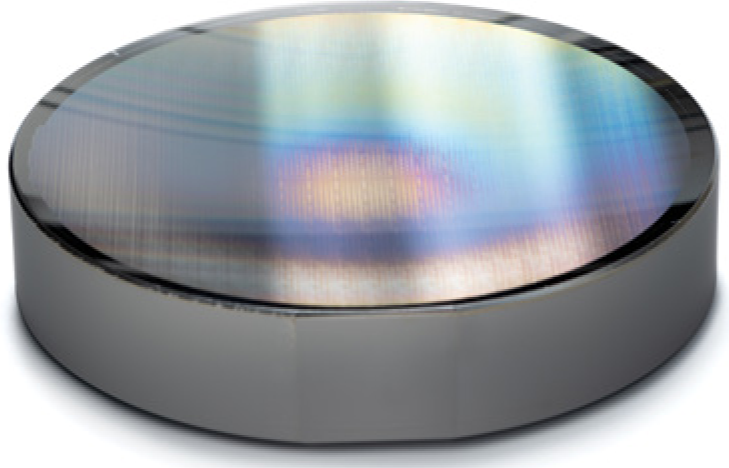
TURNING DOWN THE HEAT

TRACKING GREENHOUSE GAS EMISSIONS TO COMBAT CLIMATE CHANGE

The prototype Carbon Plume Mapper spectrometer in testing. The gold finish minimizes thermal variations in the instrument.

Methane is a potent energy-absorbing greenhouse gas in the Earth's atmosphere with many anthropogenic sources. Methane is also a comparatively short-lived gas in the atmosphere. If methane released into the atmosphere can be reduced, global warming and climate change can be slowed. Major current localized sources of methane leaks into the atmosphere are fossil fuel extraction, gas storage and transportation, landfills, and agriculture. If these sources can be rapidly identified, they can be mitigated.

A new technology has been invented at JPL called imaging spectroscopy that can measure the spectral absorption signature of methane and other compounds in the infrared portion of the spectrum as images. The methane absorption signature is weak, so the instruments need to have the exceptional light gathering capability of JPL's Dyson imaging spectrometers.



State-of-the-art JPL electron-beam-patterned Dyson grating with structured grooves to maximize efficiency in the methane portion of the spectrum.

These instruments are enabled by diffraction gratings patterned by JPL electron-beam-lithography that are the best technology available today. With this technology localized sources or plumes of methane can be identified, mapped, and mitigated.

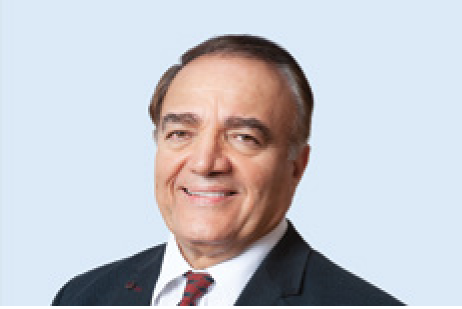
JPL imaging spectrometers flying in aircraft have demonstrated this capability by mapping methane leaks across many source domains. Once reported these leaks are usually addressed quickly and the release of methane into our atmosphere is slowed.

THE CARBON PLUME MAPPER WILL PROVIDE THE WORLD WITH A VALUABLE NEW TOOL TO FIND AND FIX METHANE LEAKS AND HELP MITIGATE GLOBAL WARMING.

To take this new technology global and turn down the heat for our planet, a public-private partnership has been formed by Carbon Mapper Inc. The partnership team will deploy a constellation of more than 20 satellites with JPL-type imaging spectrometers. Today JPL is developing the first of these instruments called Carbon Plume Mapper that will be launched in 2023. This full constellation will identify and map methane plumes around the globe at high revisit rates to provide the missing information to address this critical piece of the climate emergency.

A constellation of Carbon Plume Mapper satellites would map greenhouse gases and identify super-emitters.

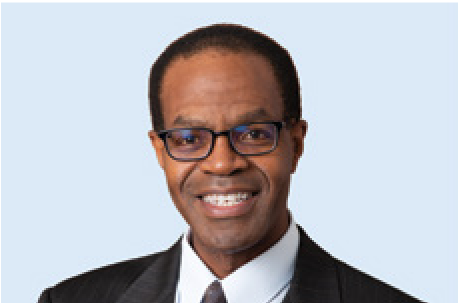
CONTRIBUTOR PROFILES



FRED Y. HADAEGH

JPL Chief Technologist

Dr. Hadaegh received his PhD in Electrical Engineering from the University of Southern California, and joined JPL in 1984. His research interests include optimal estimation and control as applied to distributed spacecraft. He has been a key contributor to G&C technologies for spacecraft formation flying and autonomous control systems for NASA missions and DoD programs. Dr. Hadaegh is a JPL Fellow, a Senior Research Scientist, Fellow of the Institute of Electronics and Electrical Engineers (IEEE), and Fellow of the American Institute of Aeronautics and Astronautics (AIAA).



CHARLES NORTON

Associate Chief Technologist

Dr. Norton holds a PhD in Computer Science from Rensselaer Polytechnic Institute and a BSE in Electrical Engineering and Computer Science from Princeton University. He has led research in high-performance scientific computing and advanced information systems, and has recently served as NASA's Special Advisor for SmallSat missions. Dr. Norton is a JPL Principal Technologist, frequent study committee member to the National Academies, and recipient of numerous awards including JPL's Lew Allen Award and the NASA Exceptional Service Medal.

BRENDAN CRILL | P.8

Principal Investigator, Coronagraph

Dr. Brendan Crill is a scientist at JPL, and as the Deputy Program Chief Technologist for the NASA Exoplanet Exploration Program (ExEP) is part of the team tasked with coordinating the development of technology to enable NASA's future exoplanet missions. He is also the Pipeline Architect for the SPHEREx mission and has a background in cosmology and astrophysics, both in science and technology.

YUNJIN KIM | P.10

Project Manager, INCUS mission

Dr. Yunjin Kim is the Project Manager of the INCUS mission. He also serves as the Directorate Engineer for the Earth Science and Technology Directorate. Dr. Kim has managed several NASA flight projects including NuSTAR and NISAR. His research interests include systems engineering, SAR polarimetry, and remotes sensing algorithms. Dr. Kim was a lecturer of Aerospace Engineering at the California Institute of Technology during the 2009 – 2012 academic years. He was the Chief Technology Officer and co-founder of Hydrosat from 2019 to 2021. Dr. Kim received his PhD in Electrical Engineering from the University of Pennsylvania in 1987.

HIRO ONO | P.12

Group Lead, Robotic Surface Mobility Group (347F), Machine Learning-based Analytics for Automated Rover Systems (MAARS)

Hiro Ono holds a Ph.D. in Aeronautics and Astronautics from MIT and is a Group Lead of JPL's Robotic Surface Mobility Group. Ono supports the Mars 2020 tactical mobility operation, developed M2020's autonomous driving algorithm, and led the landing site traversability analysis. His research interests include the application of robotic autonomy to space exploration, with an emphasis on machine learning applications. Before joining JPL in 2013, he was an assistant professor at Keio University in Japan.

ANDREA DONNELLAN | P.14

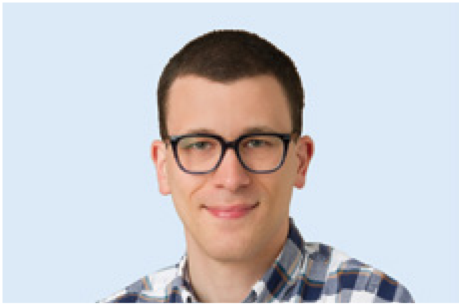
Section Manager, Instrument Systems Implementation And Concepts, Principal Investigator of the QUAKES Projects

Dr. Andrea Donnellan studies earthquake and natural hazards using remote sensing technologies. Dr. Donnellan received her MS and PhD in geophysics from Caltech. She holds a BS degree in geology from The Ohio State University and an MS in computer science from the University of Southern California. She is fellow of the American Association for the Advancement of Science and the American Geophysical Union.

SABAH BUX | P.16

Technical Group Supervisor (Thermal Energy Materials Research Group); Level 2 Technology Management Manager for the Radioisotope Power Systems Program Office

Sabah Bux received her BS in Chemistry from Cal Poly Pomona and received her Ph.D. in inorganic chemistry from UCLA. Currently she is a technical group supervisor for the thermal energy materials research group (3467). She also serves as the level 2 co-manager of the technology management portfolio for NASA's Radioisotope Power Systems (RPS) program office. She won the 2015 International Thermoelectrics Society Young Investigator award and is the 2017 recipient of the JPL Lew Allen early career award.



JEAN-PIERRE DE LA CROIX | P.18

Principal Investigator, CADRE

Dr. Jean-Pierre de la Croix is a Robotics Systems Engineer in the Maritime and Multi-Agent Autonomy group (347N). He joined JPL after completing a Ph.D. in Electrical & Computer Engineering at the Georgia Institute of Technology in 2015. His research focused on control techniques for large-scale robotic systems, such that humans can effectively interact with these systems. At JPL, he continues to work on multi-agent robotics, including CADRE, a lunar technology demonstration of multi-rover autonomy.

JOSEPH GREEN | P.20

Project Scientist, Astronomy and Physics Technology Program

Dr. Green received his PhD in Electrical Engineering from the University of Arizona with a focus on image science and image restoration. His research interests include large active optical systems, wavefront sensing and control, image super-resolution, rotating synthetic apertures, imaging and spectroscopic instrumentation. Since joining JPL in 2000, he has supported many NASA and non-NASA efforts, making significant contributions to missions including JWST, Spitzer Space Telescope and Mars Perseverance.

ROBERT SHARROW | P.22

Principal Investigator, Miniaturized X-ray Telescope for Pulsar Navigation

Robert Sharrow was responsible for leading the development of the X-ray Detector Signal Chain subsystem for the PIXL instrument on M2020, which led directly to this research effort. In his 18 years at JPL he has worked in various hardware developments for Juno, GRACE-FO, PIXL, and he now leads the development of the Europa Clipper Project Digital Sun Sensor.

JONATHAN GRANDIDIER | P.24

Principal Investigator, Low Intensity High Temperature (LIHT) Solar Cells for Venus

Dr. Grandidier is a Technologist in the Solar Array Technology and Engineering group. He is also a Visiting Associate at Caltech for the Space Solar Power Project (SSPP). He specializes in solar array, photovoltaics, power beaming and power subsystems for space applications. He was the Power Subsystem Lead for Cassini Spacecraft until the End of Mission.

APRIL JEWELL | P.26

Principal Investigator, Advanced Filter Solutions for Multiband and Broadband Imaging

Dr. Jewell is a microdevices engineer in the Advanced Detectors, Systems, and Nanoscience group at JPL. She received a PhD in chemistry from Tufts University. Her work is focused on post-fabrication processing and optimization techniques for silicon-based imagers with the goal of fine-tuning a detector's response for project- or mission-specific applications. Dr. Jewell is a 2019 recipient of JPL's Charles Elachi Award for Outstanding Early Career Achievement.

ALEX AUSTIN | P.28

Principal Investigator, Aerocapture Technology

Alex Austin is the Lead Engineer for Team Xc, JPL's formulation team for CubeSat and SmallSat missions. His research work is focused on innovative technologies and methods for performing science with SmallSats, especially in the areas of Entry, Descent and Landing (EDL) with a focus on aerocapture. He received bachelor's and master's degrees in aeronautical engineering from Rensselaer Polytechnic Institute.

ERIC KITTLAUS | P.30

Microdevices Engineer, Acousto-Optic Modulator in a Silicon Photonic Circuit

Dr. Kittlaus received his PhD in Applied Physics from Yale University. Currently, he is an engineer at JPL's Microdevices Laboratory, where he develops microwave-photonic technologies for space applications. Eric's research interests include photonics-based radars, electro- and acousto-optic device physics, integrated photonic circuits, and ultralow-noise oscillators.

COREY COCHRANE | P.32

Principal Investigator, SiCMAG

Dr. Cochrane is a member of the Advanced Optical and Electromechanical Microsystems group at JPL, with primary research interests in the measurement and study of planetary magnetic fields and plasmas. He is the calibration lead and investigation scientist for the magnetometer (ECM) and plasma (PIMS) investigations on the Europa Clipper mission. He obtained his Ph.D. degree in Engineering Science and M.S. and B.S. degrees in Electrical Engineering and Computer Science at Penn State University.

MARSHALL SMART | P.34

Principal Investigator, Advanced High Voltage, High Specific Energy and High-Power Li ion Cells with Improved Low Temperature Performance

Dr. Smart received his P.h.D in Organic Chemistry from the University of Southern California. He is currently a Principal Member of the Technical Staff and is the Cog-E of the Li-ion Battery for the Europa Clipper and Mars Helicopter projects. He researches low temperature electrolytes in lithium-ion batteries for aerospace and automotive applications. Dr. Smart developed the low temperature Li-ion electrolyte technology that was incorporated into the batteries for the MER, MSL, M2020, and InSight missions.

WEIBO CHEN | P.36

Principal Investigator, Miniature Efficient Heat Pump for Venus and Lunar Exploration

Dr. Weibo Chen has more than 20 years of research experience in heat and mass transfer, multiphase flow, cryogenics, and refrigeration cycle. He has served as Principal Investigator for dozens of aerospace R&D contracts to develop a wide range of active cryocoolers, refrigeration systems, heat pipes, pumped loops, turbomachinery, positive displacement compressors, and microchannel heat exchangers. He is currently leading the Roman CGI cryogenic thermal subsystem.

KASTHURI VENKATESWARAN | P.38

Principal Investigator, µTitan: Microgravity Tolerant InsTrument for Automated Nucleic-acid extraction

Dr. Venkateswaran is a Senior Research Scientist at JPL. He has 44+ years of research encompasses marine, food, and environmental microbiology. He leads various Space Biology and Planetary Protection projects to measure extremophilic microorganisms. He has applied his research in molecular microbial analysis to better understand the ecological aspects of microbes, by developing various instruments, while conducting field studies in several extreme environments, such as the deep sea, spacecraft missions, and the space environment in the Low Earth orbit.

MAXWELL MARTIN | P.40

Systems Engineer, 353D—Contamination Control Engineering

Mr. Martin received his BS in Materials Engineering from Cal Poly SLO and his MS in Astronautical Engineering from USC. Max is the Contamination Control lead for the Psyche and NISAR missions and supporting analysis on Mars Sample Return, Roman Space Telescope and multiple proposals. Before coming to JPL in 2017, Max led SpaceX's contamination control group and led SpaceX's materials engineering effort on the Starlink satellite program.

ELOÏSE MARTEAU | P.42

Research Technologist, Perseverance's Abrading Bit Tool

Dr Marteau received a PhD in Applied Mechanics from Caltech. She is a Research Technologist in the Robotics Modeling and Simulation group. Her research explores how robotic systems and science instruments interact with surface material on extraterrestrial bodies. She also maintains an active interest in understanding the mechanical behavior of porous media in extreme and micro-gravity environments.

VALERIE SCOTT | P.44

Microdevices Engineer, Mass Spectral Imaging

Dr. Scott is an engineer in JPL's Microdevices Laboratory and holds chemistry and biochemistry bachelor's degrees from Brandeis, a Ph.D. from Caltech in chemistry, and a master's degree in engineering from Purdue. She is the Principal Investigator of a laser-ablation mass spectrometer for isotopic dating, as well as of a miniaturized combination Mössbauer/X-ray Fluorescence spectrometer. While her primary focus is on instrument development, she also has supported broader technology and mission formulation via several different pathways, including as Chevron Technical Fellow, JPL's core A-Team, Keck Institute for Space Studies (KISS) workshop load, and STO support.

ELHAM MAGHSOUDI | P.46

Aero-Thermo Systems Engineer, Actuator

Dr. Maghsoudi (she/her) received a PhD in Thermo-fluid Science from Louisiana State University. She currently divides her time between thermal system engineering for Europa Clipper Magnetometer and deployable Magboom and developing new thermal technologies for future JPL missions. Her research interests include developing novel 3D printed heat exchangers to support a variety of applications, ranging from an active thermally controlled CubeSat to actuators on a future robotic sampling arm for use on icy moons.

MINA RAIS-ZADEH | P.48

Principal Investigator, Tunable Surface Acoustic Wave (SAW) Diffraction Grating

Mina Rais-Zadeh received her M.S. and Ph.D. degrees both in Electrical and Computer Engineering from Georgia Institute of Technology in 2005 and 2008, respectively. From 2009 to 2014, she was a faculty of Electrical Engineering and Computer Science (EECS) at University of Michigan Ann Arbor. As of 2015, she is leading the MEMS and micro-instrument development activity at JPL as a group supervisor for the Advanced Optical and Electromechanical Microsystems Group.

ELIZABETH JENS | P.50

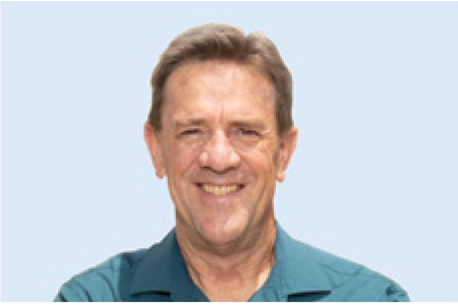
Propulsion and Systems Engineer, Martian and Lunar Dust Removal Technology

Dr. Jens earned a PhD in Aeronautics and Astronautics from Stanford University. She is the Principal Investigator for the Lunar Dust Removal Tool and the analysis lead for the Sample Retrieval Lander propulsion system. She is also active in technology development for hybrid propulsion systems and was the cognizant engineer for the gas Dust Removal Tool on the Perseverance Rover. She is the chairperson of the ASME Propulsion Technical Committee.

SARAH URDAHL STEVENS | P.52

Principal Investigator, Hardware in the Loop Testbeds for Robust Landing Navigation Systems

Sarah Urdahl Stevens received her M.S. in Aerospace Engineering from the Georgia Institute of Technology and a B.S.E. in Mechanical Engineering and Materials Science from Duke University. She is the Guidance, Navigation, and Control Flight System Systems Engineer for the Psyche Project. Sarah was previously a member of the Europa Lander Pre-Project and Mars 2020 Flight System teams. Her research interests are tied to enabling missions to poorly-mapped bodies, like Europa, by using new technologies for hazard detection and avoidance on deorbit, descent, and landing.



PAUL BACKES | P.54

Tool Development Principal Investigator, Dual Rasp: A sampling system for low-gravity environments

Paul Backes is the Group Supervisor of the Robotic Manipulation and Sampling group. He joined JPL after receiving his Ph.D. in Mechanical Engineering from Purdue University in 1987. His awards include NASA Exceptional Engineering Achievement Medal (1993), NASA Software of the Year Award (2004), IEEE Robotics and Automation Technical Field Award (2008), NASA Exceptional Service Award (2014), and 2021 Purdue University Outstanding Mechanical Engineer Alumni Award.

BORIS KARASIK | P.56

Principal Investigator, Terahertz Heterodyne Detectors

Dr. Karasik is a JPL Senior Research Scientist. His research interests include heterodyne and direct detectors based on hot-electron sensors for THz spectroscopy of interstellar gas clouds and planetary atmospheres, quantum cascade lasers, and advanced THz materials. He has led the development of novel detectors and receiver systems utilizing both superconductor and quantum-well structures.

NAN YU | P.58

Program Scientist, Group Supervisor, Senior Research Scientist, Micro Mercury Trapped Ion Clock

Dr. Nan Yu is a Senior Research Scientist, Supervisor of Quantum Sciences and Technology group, and an Adjunct Professor of Physics at the University of Southern California. He also serves as the Program Scientist for the Fundamental Physics Office. His research interests include atomic clocks, quantum sensors, photonics and nonlinear optics, and precision measurements in space.

JOHN STEEVES | P.60

Principal Investigator, Metasurface Optics for Wavefront Sensing

Dr. Steeves received his PhD in Aerospace Engineering from Caltech and is currently an optical engineer in the Advanced Deployable Structures Group. His research interests include active mirrors, wavefront sensing techniques, and optical system modeling for space-based astronomy missions. He is also a member of the Project Systems Engineering Team for the Coronagraph Instrument on the Roman Space Telescope.

SIAMAK FOROUHAR | P.62

Deputy Director of Microdevices Laboratory

Siamak Forouhar is the Deputy Director of Microdevices Laboratory with expertise in lasers and integrated photonics technologies. At his current position he contributes to setting MDL's long-term strategic direction, in line with NASA's/JPL's strategic plans to enable MDL to continue fulfilling its missions over the next decade.

DANIEL CUNNANE | P.64

Principal Investigator, Infusion of Novel Superconductors into Space Science Technology

Dr. Daniel Cunnane received his PhD in Applied Physics from Temple University studying superconducting circuits using a novel material. His end to end expertise with this material brought him to JPL in 2013 to utilize the new material for a THz mixer. Since then his research interest has been integrating novel materials to superconducting technologies for enhancing the science capabilities of future NASA instruments.

MATTHEW SHAW | P.66

Microdevices Engineer 4, Silicon Nanowire Single Photon Detectors (SNSPDs)

Dr. Shaw leads the development of Superconducting Nanowire Single Photon Detectors (SNSPDs) at JPL for applications in optical communication, quantum information science, remote sensing, dark matter detection, and astronomy. He has researched Quantum Capacitance Detectors at JPL and microwave quantum optomechanics at Caltech. Dr. Shaw is the cognizant engineer for the ground detector assemblies for NASA's Deep Space Optical Communication project and principal investigator for SNSPD technology development projects sponsored by NASA, DARPA, DOE, JPL, and other sponsors.

ADRIAN TANG | P.68

RFIC Engineer, All-Digital/Reconfigurable CMOS Ground Penetrating Radar System on a Chip

Adrian is a staff researcher at JPL, and associate researcher at the University of California, Los Angeles. His research focuses on architecture and implementation of mixed-signal, digital, and mm-wave system-on-chip (SoC) design with an emphasis on high-speed circuit topologies and techniques. At JPL he develops CMOS SoCs for radar, radiometer and spectrometer instrumentation.

ALI AGHA | P.70

Research Technologist and Group Leader, NeBula Systems

Dr. Agha is a Technologist and Group Leader at JPL's Autonomous and Robotic Systems Division. Previously, he was with Qualcomm Research and MIT, leading the perception efforts for self-flying drones and autonomous cars. His research interests include AI, autonomous decision making, and perception for robotic systems, with applications to legged robots, rovers, drones, and self-driving off-road vehicles. Dr. Agha was named NASA NIAC fellow in 2018 and was a recipient of the Lew Allen Award.

DAVID WEBB | P.72

Mechanical Lead, S5—Starshade to Technology Readiness Level 5

Mr. Webb is a Product Delivery Manager (PDM) in the Mechanical Systems group and currently serves as a PDM on the Mars Ascent System Payload on Mars Sample Return. His work on S5 ended in 2021 with the successful completion of the first set of S5 mechanical milestones.

ROBERT O. GREEN | P.74

Instrument Scientist, Carbon Plume Mapper

Dr. Robert O. Green is the Instrument Scientist for Carbon Plume Mapper that will be used to identify and mitigate localized sources of methane. He is the Principal Investigator of the Earth Surface Mineral Dust Source Investigation that will fly a state-of-the-art imaging spectrometer on the ISS. He is the Principal Investigator of AVIRIS that is used for advanced science and applications research across the Earth system. Dr. Green is a Co-investigator for the Lunar Trailblazer and Mapping Imaging Spectrometer for Europa missions. For more than 25 years, his research focus has been to use advanced imaging spectroscopy for science and discovery on Earth and through the solar system.

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About this page: A close up image of a Dyson grating with structured grooves. See page 75.