National Aeronautics and
Space Administration

2020 TECHNOLOGY HIGHLIGHTS

Jet Propulsion Laboratory

Jet Propulsion Laboratory Technology Highlights 2020

National Aeronautics and Space Administration

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TECHNOLOGY DRIVES EXPLORATION

This JPL 2020 Technology Highlights presents a diverse set of technology developments—selected by the Chief Technologist out of many similar efforts at JPL—that are essential for JPL's continuing contribution to NASA's future success. These technology snapshots represent the work of individuals whose talents bridge science, technology, engineering, and management, and illustrate the broad spectrum of knowledge and technical skills at JPL. While this document identifies important areas of technology development in 2019, many other technologies remain equally important to JPL's ability to successfully contribute to NASA's space exploration missions, including mature technologies that are commercially available and technologies whose leadership is firmly established elsewhere.


About the cover: the Mars Helicopter, known as Ingenuity, is set to perform the first powered flight on another world.

OFFICE OF THE DIRECTOR

As NASA's leading center for robotic exploration of the universe, JPL develops technologies that advance our pursuit of discoveries to the benefit of humanity. Although our technologies are to enable science, they often have dual use for commercial and urgent societal needs.

Despite the pandemic, JPL accomplished its biggest goal of 2020. The next Mars rover, Perseverance, is healthy and well on its way to the Red Planet. Perseverance carries Ingenuity, also known as the Mars Helicopter: the first system to fly on another world. The children who named Perseverance and Ingenuity could not have known how fitting those names would prove in 2020.

In the past 12 months, the Orbiting Carbon Observatory 3 began its mission to continue global OCO-2 carbon dioxide measurements from the ISS in conjunction with other ISS instruments; the Deep Space Atomic Clock mission launched and demonstrated miniaturized and ultra-precise timing technology enabling future spacecraft to independently navigate in deep space without ground intervention; and SPHEREx was selected as a future near-infrared space observatory that will perform an all-sky survey to measure the near-infrared spectra of approximately 450 million galaxies.

Prioritizing technology development and infusion has always been a crucial piece of the Laboratory's mission success. No one has tried to dig kilometers through the icy crust of a Jovian moon; no one knows the true nature of dark matter and energy; none of us have seen the oceans and continents of another habitable world. The ambition and vision necessary to invent the technologies that will enable such goals has never ceased to surprise and impress me. Every example in this book exemplifies JPL's long history as a center of excellence for research and technology development.

Welcome to the latest edition of JPL Technology Highlights. I invite you to escape the present, for a moment, by exploring the future of breakthrough technologies in space and on Earth.

MIKE WATKINS

JPL DIRECTOR

ON THIN AIR

The first helicopter designed to fly on another planet is, at time of publication, on its way to Mars. The Mars Helicopter, Ingenuity, is hitching a ride with the Mars 2020 Perseverance rover, which lifted off on an Atlas V rocket from Florida's Cape Canaveral Air Force Station on July 30. "This will actually be very much a Wright Brothers moment, except on another planet," Mimi Aung, Project Manager for Ingenuity, said in a news conference on July 28.

On Mars the atmosphere is 99% thinner than on Earth, which means 99% less air to generate lift, and more technical challenges in staying aloft. Ingenuity weighs about 4 lbs. (1.8 kilograms) and has two counter-rotating blades that measure about 4 feet (1.2 meters) long. Those specially made carbon-fiber blades should spin at a rate of about 2,400 revolutions per minute, according to tests run in a chamber simulating the Martian atmosphere.

Communication delays across interplanetary distances mean commands need to be sent in advance, as engineering data will come back from the spacecraft long after each flight takes place. Ingenuity will need to autonomously make its own decisions about how to fly to a waypoint and keep itself warm. These technologies could enable other advanced robotic flying vehicles that might be included in future robotic and human missions to Mars.

NASA's Mars 2020 Perseverance rover and NASA's Ingenuity Mars Helicopter, shown in an artist's concept.

OFFICE OF THE CHIEF TECHNOLOGIST

Our daily reliance on the impact and benefits of technology has never been clearer. Science and engineering, enabled by new technologies, form the tools to help us adapt to the world's emergent challenges. At JPL, we develop technology as the underlying capability to bring new discoveries to the world.

The JPL Technology Highlights collection represents only a small part of JPL's technology portfolio. Autonomy will allow robotic exploration platforms to explore while independently detecting and prioritizing science targets set by scientists. Rovers will coordinate among themselves to peer through kilometers of ice and snow. Wheels will feel the ground they roll upon. Technologies to search for and detect life around the solar system will become small enough to support large-scale highly distributed mission systems. Novel materials and manufacturing techniques will allow for new instrument and platform architectures. All these capabilities are enabling new thinking on how best to explore our universe.

JPL's diverse research and technology development community has gone above and beyond at the time of my writing this letter to you. The ingenuity displayed by JPL technologists in responding to the world's most challenging questions during the COVID-19 pandemic demands recognition. The VITAL ventilator highlighted in this book is just one of several efforts taking place at the Laboratory to help us navigate the pandemic, including new types of personal protective equipment based on 3D printing, and wearable technology.

With this 2020 edition of Technology Highlights, I invite you to explore its pages further, joining us in our journey of discovery that embraces the opportunities that the future presents.

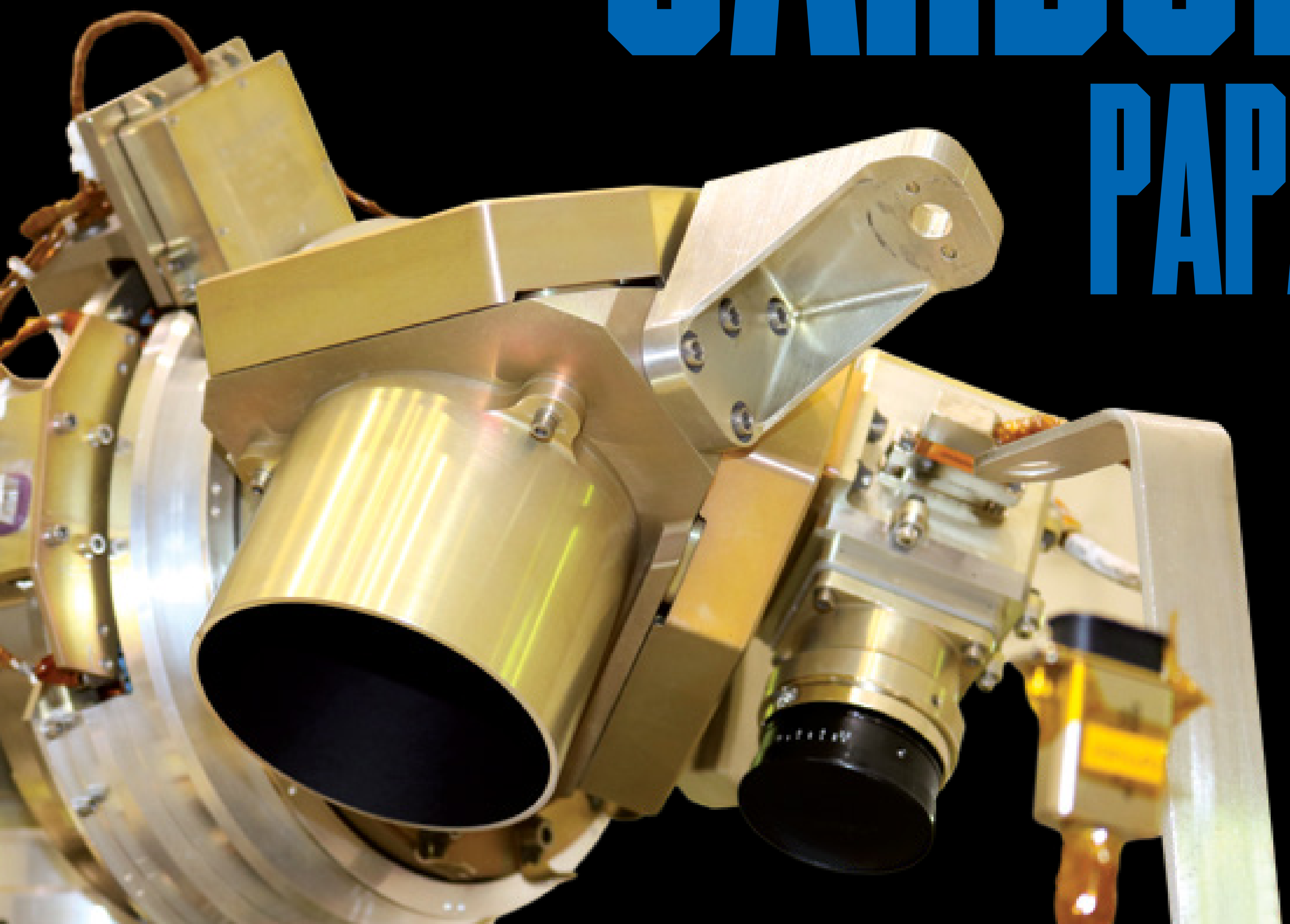
FRED HADAEGH
JPL CHIEF TECHNOLOGIST

CARBON PAPARAZZI

01

Observing the rise and fall of carbon dioxide

Closeup of the Orbiting Carbon Observatory-3 showing the pointing mirror assembly (left) and external context camera (right).



View of Earth from the International Space Station, where the Orbiting Carbon Observatory-3 is installed.

ORBITING ON THE INTERNATIONAL SPACE STATION, THIS CARBON OBSERVATORY SHOWS HOW THE EARTH — CITIES, FIELDS, OCEANS, VOLCANOES, AND ALL — BREATHES.

Humans produce billions of tons of extra carbon dioxide a year. Scientists are measuring carbon dioxide levels to monitor changes in the Earth's carbon cycle. Most measurement systems, such as those in polar orbit, gather data from the same locations, at the same time each day. However, we know that carbon dioxide levels rise and fall throughout the day. Tracking this daily shift would teach us more about how emissions and photosynthesis affect carbon levels.

The Orbiting Carbon Observatory-3 (OCO-3) was launched on May 4, 2019, and began its three-year prime mission in September 2019. OCO-3 provides scientists the ability, for the first time, to observe how carbon dioxide levels in the atmosphere shift throughout the day, across the globe. Traveling along the International Space Station's multiple orbits from London to Patagonia, the remote sensing system measures carbon levels a little earlier on each orbit. The observatory spans all sunlit hours within about a month.

A single telescope takes light in, then a series of filters split the light into three different wavelengths. Three high-resolution spectrometers work together to measure carbon levels: one measures how much sunlight oxygen absorbs, and the others measure how much sunlight carbon dioxide absorbs at two different wavelengths. Two high-resolution context cameras provide pointing information, images of the ground for measurement context, and show cloud coverage, all to help pick the best carbon snapshots. OCO-3's agile two-axis Pointing Mirror Assembly can repoint the instrument in just 5 to 15 seconds. The observatory produces dozens of 80 km x 80 km "snapshot area maps" each day.

OCO-3 also studies Solar-Induced Fluorescence: radiation emitted by plants during photosynthesis, when turning sunlight and carbon into energy. The more efficiently a plant absorbs carbon dioxide, the more radiation it emits. Seeing how plants 'breathe' with photosynthesis is key to understanding Earth's carbon cycle. Understanding how photosynthesis adapts to a changing climate could help us better understand how to adapt ourselves.

How carbon dioxide comes and goes is especially useful when combined with data on other systems the carbon cycle interacts with, such as ocean, wind, or atmospheric humidity data. That impacts everything from climate modeling and weather prediction to conservation and crops.

Shown above is the fully integrated Faint Intergalactic-medium Redshifted Emission Balloon 2 (FIREBall-2) spectrograph, sealed, and in operation.

02

Nano technologies reveal the universe's largest structures

EXPLORING THE UV-VERSE

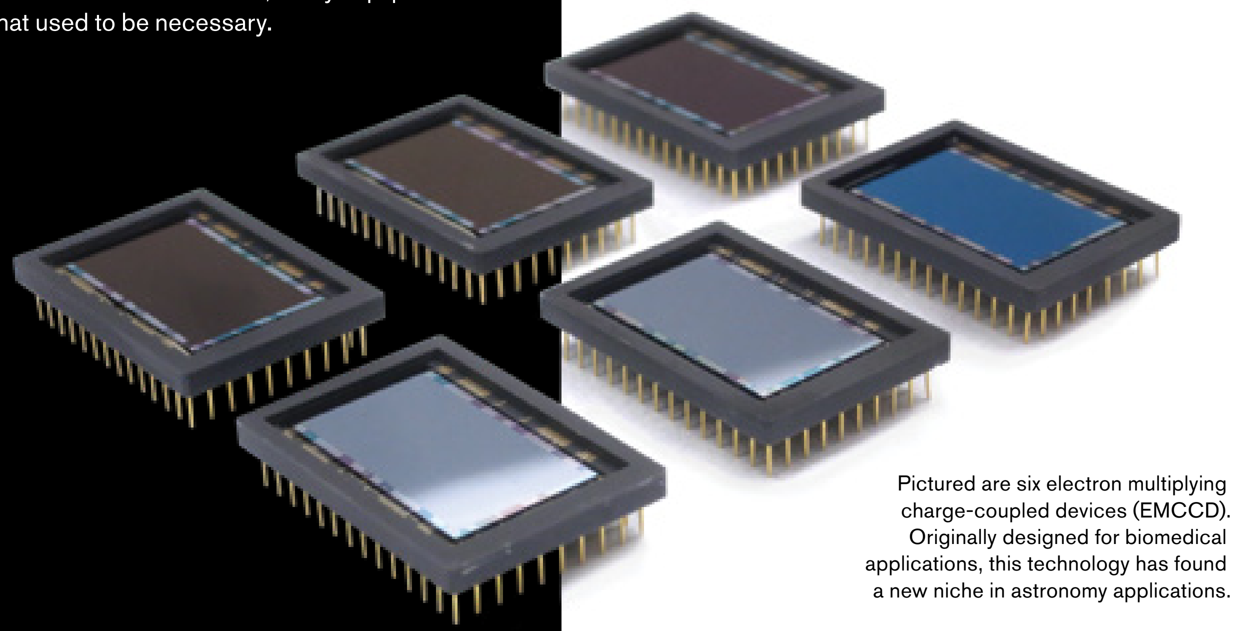
Ultraviolet (UV) light is found throughout the universe, produced by stars, like the Sun, supermassive black holes, and even planetary atmospheres. UV radiation can only be observed from space, because it is absorbed by Earth's atmosphere. UV radiation has unveiled "stellar nurseries," water on planetary bodies, and the largest spiral galaxies ever seen. Observing the structure and behavior of star-forming gases in UV, over a range of redshifts in both emission and absorption, will give us insight into the evolution of the galaxies in our cosmos.

The Faint Intergalactic-medium Redshifted Emission Balloon 2 (FIREBall-2) launched into Earth's stratosphere carrying the first space-bound 2D-doped Electron Multiplying Charge-Coupled Device (EMCCD). This UV telescope uses 2D-doped EMCCDs tailored using nano-engineering in order to observe galaxy UV emissions with high sensitivity, and without most of the extra, bulky equipment that used to be necessary.

Ordinary CCDs, like the one on Hubble, collect light and convert it to digital readouts to produce images. EMCCDs include an additional level of internal registers to amplify the electrons produced by the light (hence "electron multiplication" in its name) and thereby enabling seeing very faint light. EMCCDs were originally designed for biomedical applications such as probing cell growth rates. The design has been adapted for astronomy and astrophysics for extremely low light level imaging, enabling devices which can operate in low lighting, with unprecedented high sensitivity, and at the same high speeds.

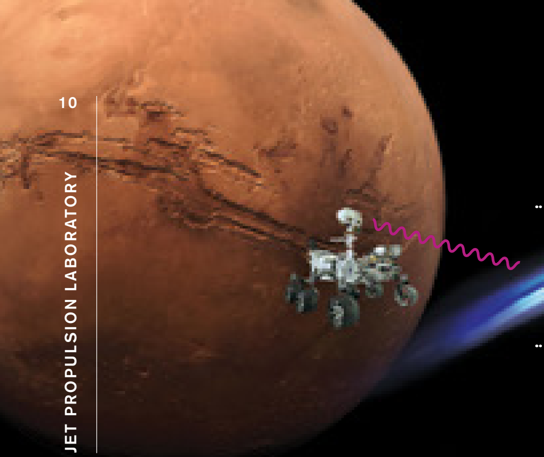
Advanced nano-engineering techniques were used to optimize this EMCCD for UV detection, delta-doping and custom atomic-level controlled antireflection coatings. The improved telescope is 30 times more sensitive than its predecessor FIREBall-1. This capability allows future telescopes to be four times smaller, with ten times improved performance. FIREBall-2 is the first telescope of its kind attempting to image the 3D structure of galactic surroundings.

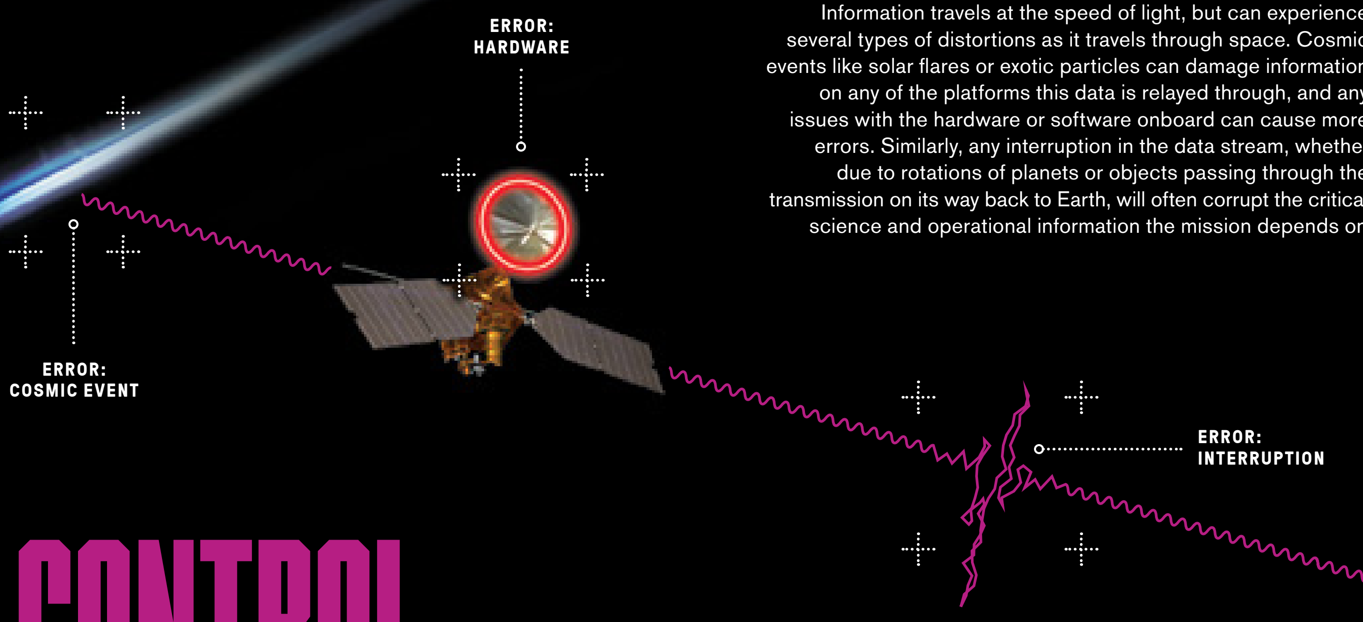
These missions serve to demonstrate 2D-doped EMCCDs in a space environment, allowing future flagship missions such as the Large Ultraviolet Optical Infrared Surveyor (LUVOIR) or Habitable Exoplanet Mission (HabEx) to utilize proven, high-performing UV detectors. This particular advance also has applications in biomedical research such as imaging a single molecule.



Pictured are six electron multiplying charge-coupled devices (EMCCD). Originally designed for biomedical applications, this technology has found a new niche in astronomy applications.

FIRST SPACEBORNE EMCCDs (ELECTRON MULTIPLYING CHARGE-COUPLED DEVICE) RELY ON 3 ADVANCES: SINGLE PHOTON COUNTING, 2D DELTA DOPING, AND ATOMIC LAYER DEPOSITION.





Information travels at the speed of light, but can experience several types of distortions as it travels through space. Cosmic events like solar flares or exotic particles can damage information on any of the platforms this data is relayed through, and any issues with the hardware or software onboard can cause more errors. Similarly, any interruption in the data stream, whether due to rotations of planets or objects passing through the transmission on its way back to Earth, will often corrupt the critical science and operational information the mission depends on.

GROUND CONTROL TO MARS AI

03

AI finds data errors quickly, reliably, so rovers can go faster

Even the slightest gap or error in knowledge when operating on another planet can lead to critical failure. Rovers like Curiosity, or this year's Perseverance, enable the most in-depth exploration of the Martian surface. Dozens of cameras, sensors, and instruments on a 6-wheel Jeep-sized robot work together to collect new data on Martian mysteries. This data, as well as operational data about the rover itself, follows a multi-stage transmission path: from the rover to satellites orbiting Mars, to Deep Space Network stations back on Earth, and finally to Mission Control. Data can be interrupted or corrupted at any of these stages, limiting the data's usefulness. Ground analysts must scour this deluge of downlinked data to find these interruptions, determine their root causes, and correct them before sending any new commands, like moving or using an instrument. With such refined technology, so far from Earth, any mistake can be mission critical.

AUTOMATED DATA ACCOUNTABILITY FOR MISSIONS DETECTS ANOMALIES IN MARS ROVER DATA: ANALYSTS USED TO LOSE CRITICAL MANEUVERING TIME JUST *LOOKING* FOR ERRORS.

MARS MISSION CONTROL

The Automated Data Accountability for Missions (ADAM) algorithm diagnoses data fidelity issues accurately and automatically, thanks to an emerging technology: adversarial autoencoders. ADAM combines two other state-of-the-art machine learning techniques: autoencoders and generative adversarial networks (GAN). An autoencoder compresses and decompresses data and checks that the data looks the same on each side of the process. GANs are two neural networks, a generator and a discriminator, that compete with each other during training. The generator creates 'fake' data which is passed to the discriminator. The discriminator learns to tell between 'real' and 'fake' data. As the discriminator improves, so does the generator. An adversarial autoencoder is a GAN where both the generator and discriminator are autoencoders.

When demonstrated on real Mars data in 2019, this tool showed a 93% recall rate on incomplete passes as compared to the current rate of 55%—while also reducing the number of false alarms. The algorithm increases scientists' ability to use incomplete Curiosity data by 40%. This technology is now being used on mission, every day.

Although designed with the Curiosity rover in mind, this tool can easily be applied to many areas of ground operations for any mission. Fast, automated anomaly detection supports planning, sequencing, spacecraft health monitoring, and accurate science. The tool can also be adapted for use helping spacecraft operate more autonomously, as future missions will need to. Technology that efficiently verifies data is increasingly critical for a variety of applications.

04

READY, AIM, FLY

Tube-shot drones can deploy safely, rapidly, and from unstable platforms

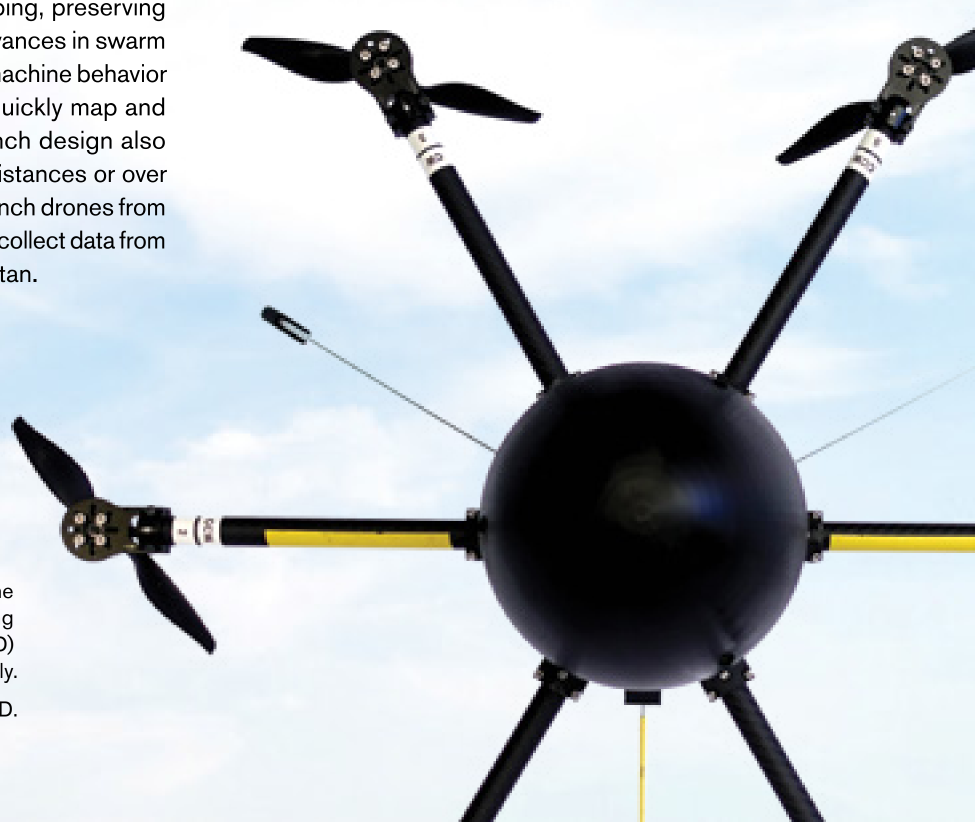
Drones are becoming ubiquitous, from shipping and delivery, aerial photography, weather forecasting, search and rescue, and even planetary exploration. However, takeoff remains a challenge that can restrict the usefulness of drones in difficult situations. Current designs are slow to deploy, requiring user intervention and a stable takeoff platform. Obstructions, uneven terrain, animals, and winds all present collision hazards to the drone itself, nearby assets, and people. These complications can make takeoff dangerous or even impossible—often in situations where safe, rapid takeoff is especially critical.

The Streamlined, Quick-Unfolding Investigator Drone (SQUID) is a tube-launched multi-rotor drone that eliminates the need for a user or stationary takeoff pad. The drone is fired from a cannon, automatically unfolds, and follows a desired trajectory. The ballistic launch prevents collision hazards by determining a path for the drone away from other assets. With this capability, drones can be launched from moving platforms safely, and in various environments.

Three variations of SQUID have been developed to date—sized for 3-inch, 4-inch, and 6-inch diameter tubes, with progressively increasing capability and autonomy. To launch, the drone deploys from a high-pressure gas launcher. Spring-loaded fins and arms rapidly unfold in mid-air in less than a tenth of a second. SQUID transitions to stable flight in less than a second after launch, even in the face of strong winds—autonomously—with an aerodynamic stabilization system that doubles as landing gear. The largest SQUID prototype includes full onboard estimation, which allows SQUID to control its position and fly along a desired path, even without GPS.

This is the first multi-rotor ballistic drone, which is easier to fly and more maneuverable than other tube-launched drones. The 3D printed and carbon-fiber design has enough thrust to carry payloads while withstanding launch loads. The fabricated system has been field-tested from a moving vehicle up to 50mph/80km/h, demonstrating the design's aerodynamic stability and deployment reliability.

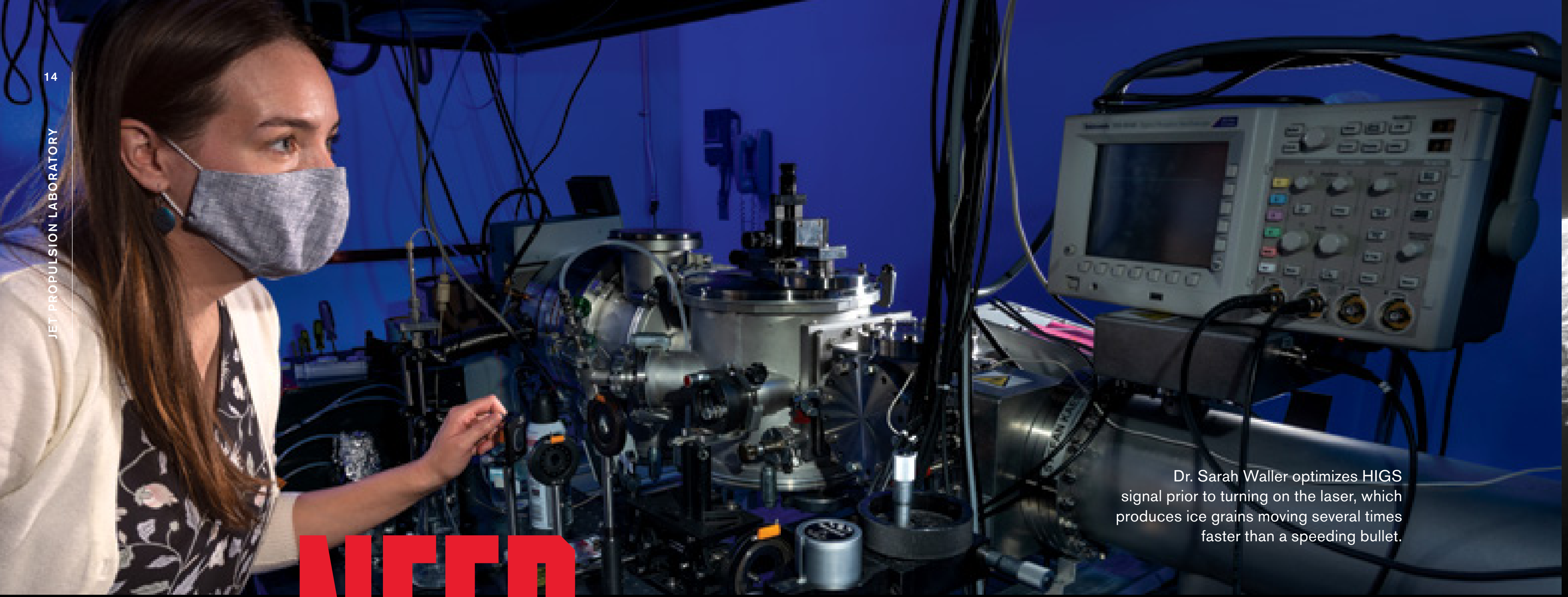
This technology has significant applications for emergency situations and planetary exploration. Drones scout for emergency responders, offering critical situational awareness such as the safe path forward in disaster zones. Ballistic takeoff allows emergency teams to launch drones from moving vehicles without stopping, preserving precious time. For example, advances in swarm technologies and coordinated machine behavior could enable many SQUID to quickly map and monitor a wildfire. SQUID's launch design also allows for deployment at longer distances or over steep terrain. We could one day launch drones from landers, rovers, and entry vehicles to collect data from sites on bodies such as Mars and Titan.



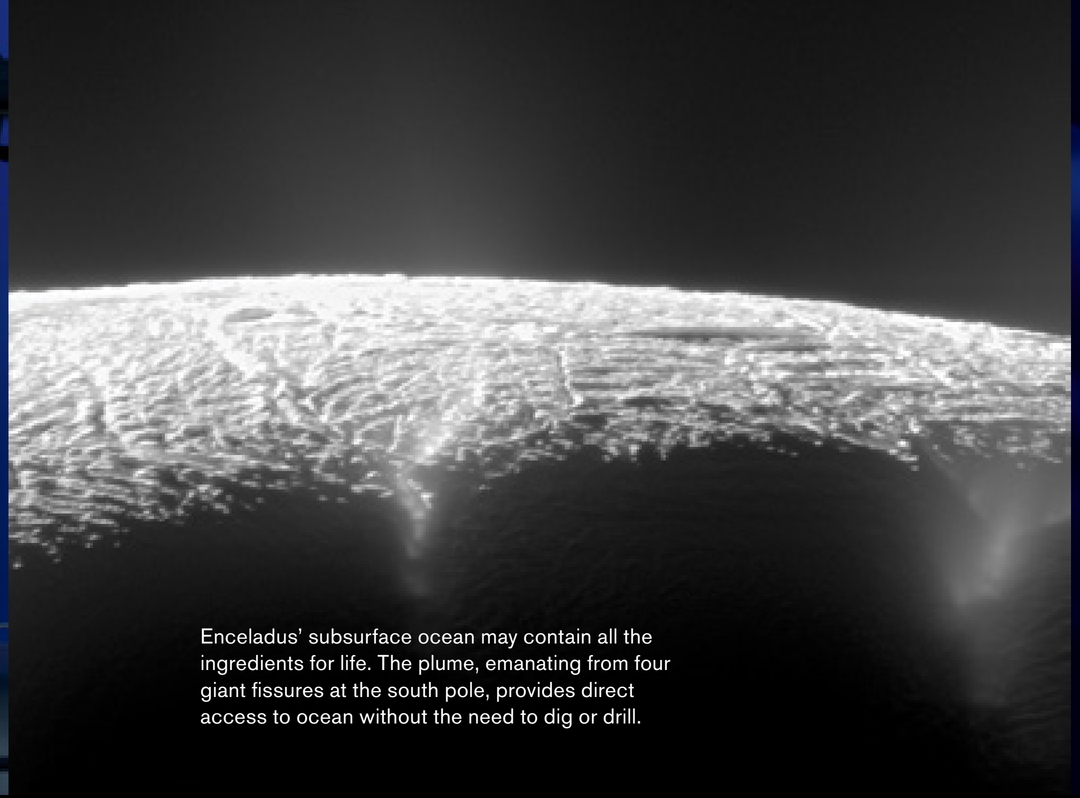
Left: Image series showing the Streamlined, Quick-Unfolding Investigator Drone (SQUID) being launched ballistically.

Right: Overhead view of SQUID.

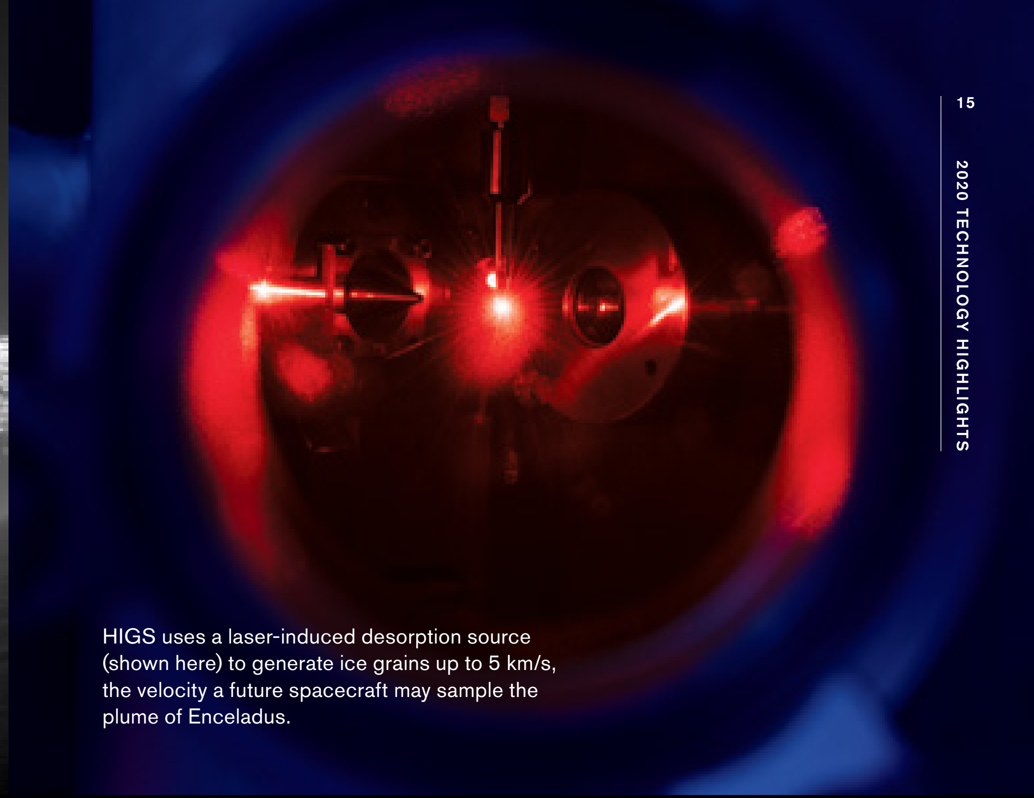
SQUID HAS SPRING-LOADED FINS AND ARMS THAT UNFOLD IN MID-AIR BEFORE TRANSITIONING TO AUTONOMOUS STABLE FLIGHT: NO USER REQUIRED.



Dr. Sarah Waller optimizes HIGS signal prior to turning on the laser, which produces ice grains moving several times faster than a speeding bullet.



Enceladus' subsurface ocean may contain all the ingredients for life. The plume, emanating from four giant fissures at the south pole, provides direct access to ocean without the need to dig or drill.



HIGS uses a laser-induced desorption source (shown here) to generate ice grains up to 5 km/s, the velocity a future spacecraft may sample the plume of Enceladus.

NEED FOR SPEED

05

Hypervelocity flybys can search for life without landing

800 million miles away, giant geyser-like jets of water and ice are shooting out of Enceladus at several hundred mph. This moon of Saturn conceals a subsurface ocean that may contain all the ingredients for life. Enceladus became another potential target of astrobiology exploration when the Cassini spacecraft flew through the plumes of water several times to collect a sample and discovered some of the ice grains contain a lot of organic molecules. These eruptions can tell us what is underneath kilometers of ice without a drill.

To analyze these ice grains for signs of life, a flyby mission would need to conduct plume sampling at hypervelocity—more than twice as fast as a speeding bullet. Upon impact at such high speeds, most molecules in the grain will go from solid to vapor phase, and can ionize or fragment in the process. Scientists need to determine the best speeds for sampling these ice grains without damaging the organic matter inside.

The Hypervelocity Ice Grain System (HIGS) is designed to test hypervelocity sampling of ice grains. The system is an advanced ice grain accelerator capable of surpassing hypervelocity—typically defined as 3 km/s (or 6,711 mph). HIGS uses laser-induced desorption to generate multiple ice particles of different sizes at once. These particles are made to a specific composition and size range to simulate the ice grains found in the plume of Enceladus. The laser-induced desorption process is so energetic that it accelerates these grains to hypervelocity, allowing scientists to analyze their behavior at these high speeds.

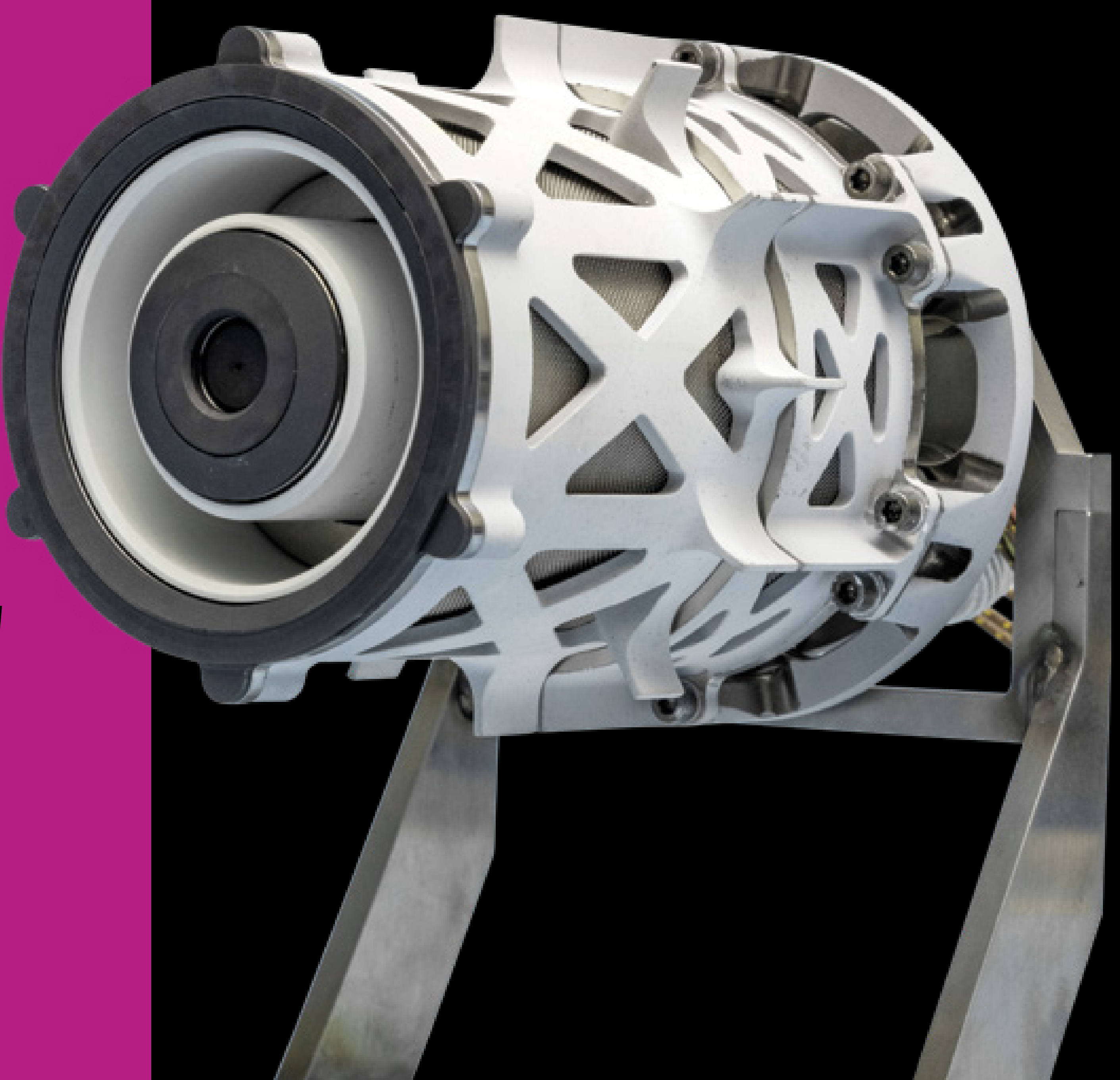
The search for life requires the same ingenuity and adaptability that life itself shows. Ultimately, HIGS will be coupled to mass analyzers such as JPL's Quadrupole Ion Trap Mass Spectrometer (QITMS). Together, these systems will characterize the response and survivability of different organic species within the ice. Engineers are also developing methods to soften ionization after a hypervelocity impact in the QITMS. These efforts represent a strong start to understanding hypervelocity sampling, which will inform design, planning, and implementation of future mission concepts to Enceladus. Jupiter's moon, Europa, another candidate for hosting life, likely has plumes. The same technology would also work to analyze comet tails, or even the atmospheres of gas giants. As the first and only U.S. facility capable of performing experiments on multiple ice grains simultaneously, HIGS will give us a new way to search for life in the solar system.

THE HYPERVELOCITY ICE GRAIN SYSTEM WILL HELP TUNE THE VELOCITY OF SPACECRAFT FOR THE DETECTION OF BIOSIGNATURES IN GRAINS OF ICE SHOOTING FROM OCEAN WORLDS.

Propelling the SmallSat revolution

SLOW AND LOW

06



SmallSats are an exciting prospect for interplanetary exploration. Small and affordable spacecraft could change the way NASA explores, enabling more small missions to more destinations. Interplanetary spacecraft like DAWN relied on electric propulsion (EP) to travel through deep space, with missions typically spanning years. Due to weight and power restrictions, SmallSats cannot use conventional EP. They require a small, low power, and highly efficient propulsion system with a multi-year operational lifetime.

The Ascendant Sub-kW Transcelestial Electric Propulsion System (ASTRAEUS) is like a car engine for SmallSats. Central to this system is the Magnetically Shielded Miniature (MaSMi) Hall thruster. Instead of pistons and petroleum, Hall thrusters use magnetic and electric fields to ionize and accelerate propellant to produce thrust. Low thrust over long periods of operation generates consistent and efficient propulsion. MaSMi is roughly the size of a soda can—just right for SmallSats.

A major shortcoming of conventional Hall thrusters is a short lifetime, caused by the thruster's own plasma eroding the components. Magnetic shielding prevents erosion by containing the plasma away from key thruster surfaces. MaSMi's magnetic field topology reduces erosion rates >10-100 times compared to conventional Hall thrusters, extending its life by the same factor over previous devices.

The most recent MaSMi iteration incorporates two new features to further boost performance: an internally mounted hollow cathode and propellant distributor with exceptional flow uniformity, both of which enhance efficiency. With these features, MaSMi surpasses the efficiency and lifetime of any prior low-power Hall thruster. Conventional sub-kW thrusters typically have less than 50% total efficiency and maximum lifetimes of a few thousand hours. In contrast, MaSMi has demonstrated 54% total efficiency and has a predicted lifetime (based on short-duration wear tests and plasma modeling) of tens of thousands of hours.

With ASTRAEUS and MaSMi, SmallSats can efficiently travel across the entire solar system and execute time-critical maneuvers such as orbit insertion, or cruise with precise, long duration applications of low thrust. Planetary scientists can leverage this low-cost option to conduct more missions than ever before, growing our understanding of the origins and workings of the universe.

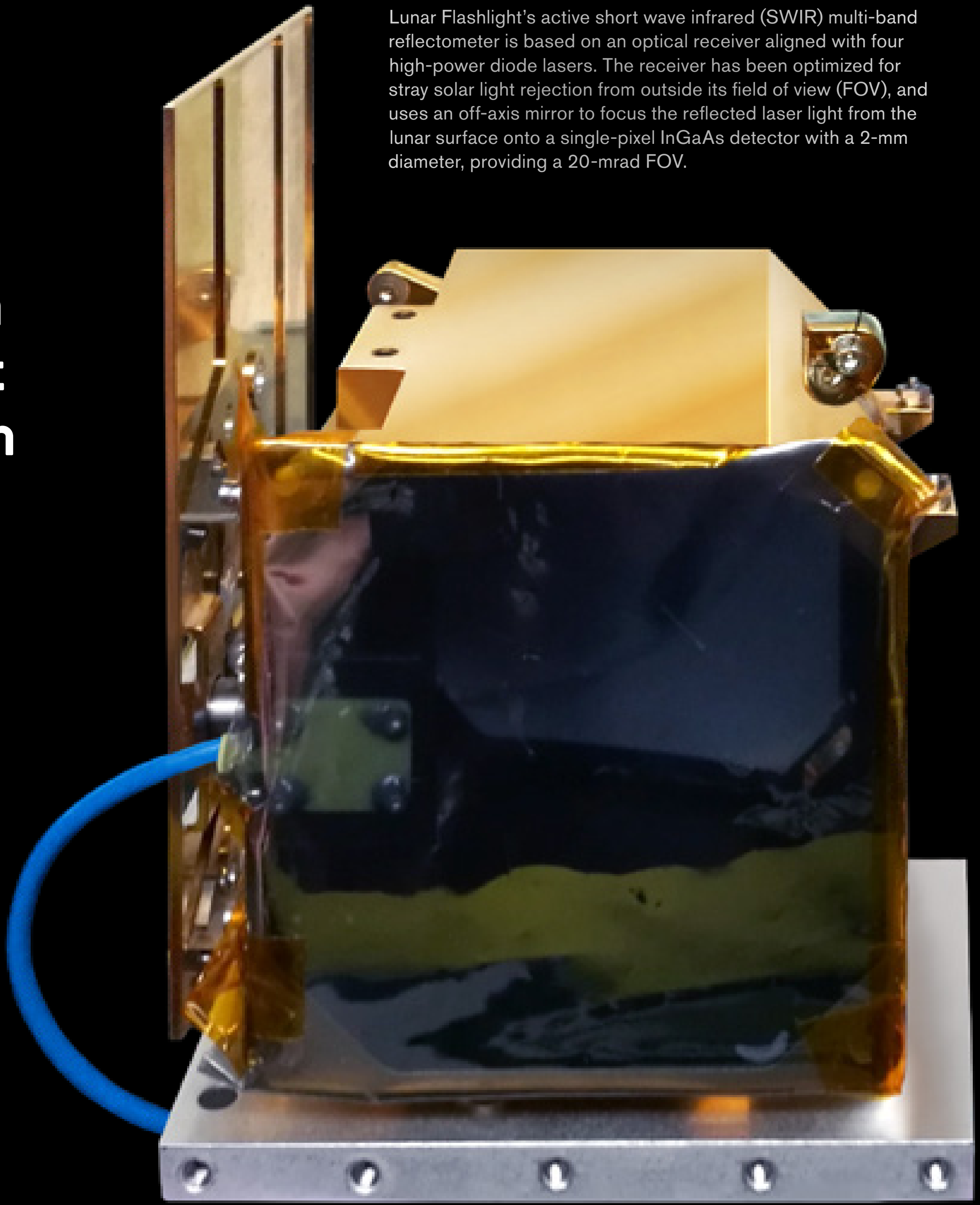
MASMI EXTENDS THE LIFETIME OF THE WORLD'S HIGHEST EFFICIENCY LOW-POWER HALL THRUSTER AT LEAST 10 TIMES, PUSHING SMALLSATS THROUGH MULTI-YEAR JOURNEYS ACROSS THE SOLAR SYSTEM.

During characterization testing, as seen here, the MaSMi-DM demonstrated thrusts of up to 68.6mN of thrust, total specific impulse of up to 1940 s with 1500 s available at 500W, and total efficiencies of up to 54.2% with 40% available at >300W. These numbers show that MaSMi-DM, as seen on the left, is the highest efficiency, highest Isp subkW Hall thruster (magnetically shielded or unshielded) developed to date.

MOON SHINE

07

Shining a spotlight on hidden lunar ice



Lunar Flashlight's active short wave infrared (SWIR) multi-band reflectometer is based on an optical receiver aligned with four high-power diode lasers. The receiver has been optimized for stray solar light rejection from outside its field of view (FOV), and uses an off-axis mirror to focus the reflected laser light from the lunar surface onto a single-pixel InGaAs detector with a 2-mm diameter, providing a 20-mrad FOV.

NASA is gearing up for sustained human presence beyond low Earth orbit. Future missions to the Moon will last longer than before, going from days to weeks. Astronauts will need to use whatever local resources they can. Scientists believe the Moon has harvestable ice water, which can be turned into drinking water or fuel. But before they can mine the ice, they need to confirm its location, quality, and quantity.

The Lunar Flashlight mission is a SmallSat designed to map ice on the Moon. Over the course of two months, the satellite will see into permanently shadowed craters at the Moon's South Pole and search for hidden surface ice. These craters are believed to be "cold traps" that harbor ice molecules shed from comets and asteroids, accumulated over billions of years. The chemical composition of this ice may be preserved from eons past, giving scientists clues about the early solar system.

The satellite shines lasers into these craters, and a unique onboard reflectometer measures the surface reflection. The short wave infrared (SWIR) multi-band reflectometer is based on an optical receiver aligned with four high-power (14-71.5 W) diode lasers emitting in the 1 to 2 micrometer shortwave infrared band. It measures the reflectance of the lunar surface near water ice absorption peaks. If present, ice will absorb the laser light—the more absorption, the more ice.

The receiver has been optimized to reject stray solar light from outside its field of view, since this can completely throw off its measurements. The multi-band SWIR reflectometer uses an off-axis mirror to focus the reflected laser light from the lunar surface onto a single-pixel InGaAs detector with a 2-mm diameter, which provides a 20-mrad field of view. The selected orbits allow the spacecraft to scan 2.28 km/second on average, corresponding to 4.4 seconds of integration time every 10 km. Combining the data from Lunar Flashlight with that gathered from other Moon-orbiting missions would provide a global view of the Moon's surface ice.

The mission will mark a few other technological firsts. It will be the first mission to look for ice with lasers. The instrument will be the first aboard a SmallSat to operate beyond low Earth orbit, demonstrating a low-cost option for scientific measurements in space. The satellite will also be the first planetary spacecraft to use "green" propellant, a new fuel that is safer and less toxic than traditional spacecraft propellant.

LUNAR FLASHLIGHT'S MULTI-BAND SHORT WAVE INFRARED REFLECTOMETER USES MULTIPLE LASERS TO DETECT WATER ICE, AND AN OFF-AXIS MIRROR TO FOCUS THE LIGHT.

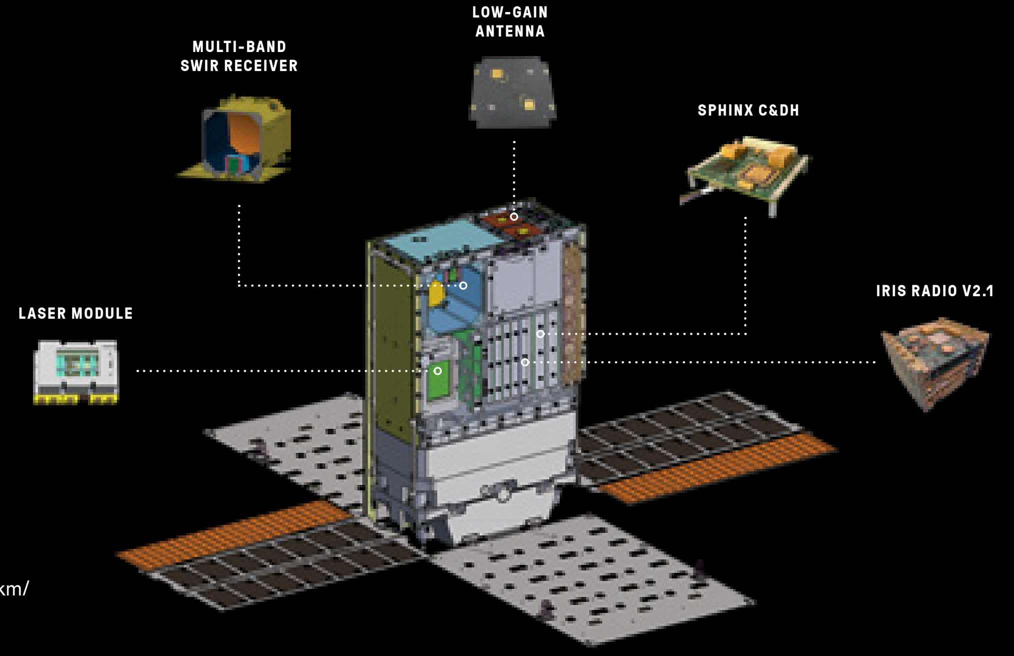
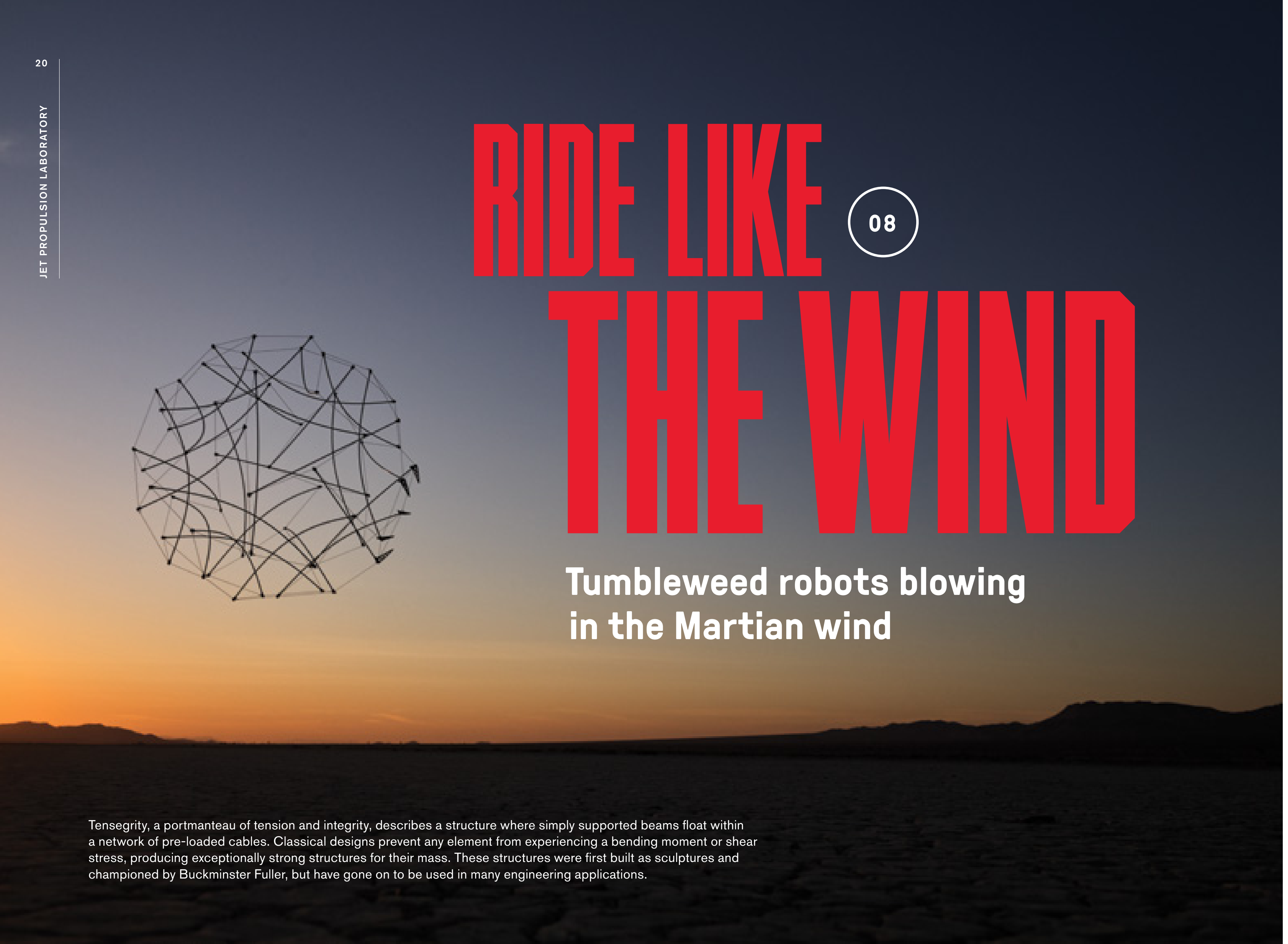


Diagram of Lunar Flashlight showing key components of this technology demonstration mission with science objectives. Lunar Flashlight will be the first SmallSat mission to use lasers to look for ice on the Moon. The selected orbits allow the spacecraft to scan 2.28 km/second on average, corresponding to 4.4 seconds of integration time every 10 km.



RIDE LIKE THE WIND

08

Tumbleweed robots blowing in the Martian wind

Tensegrity, a portmanteau of tension and integrity, describes a structure where simply supported beams float within a network of pre-loaded cables. Classical designs prevent any element from experiencing a bending moment or shear stress, producing exceptionally strong structures for their mass. These structures were first built as sculptures and championed by Buckminster Fuller, but have gone on to be used in many engineering applications.

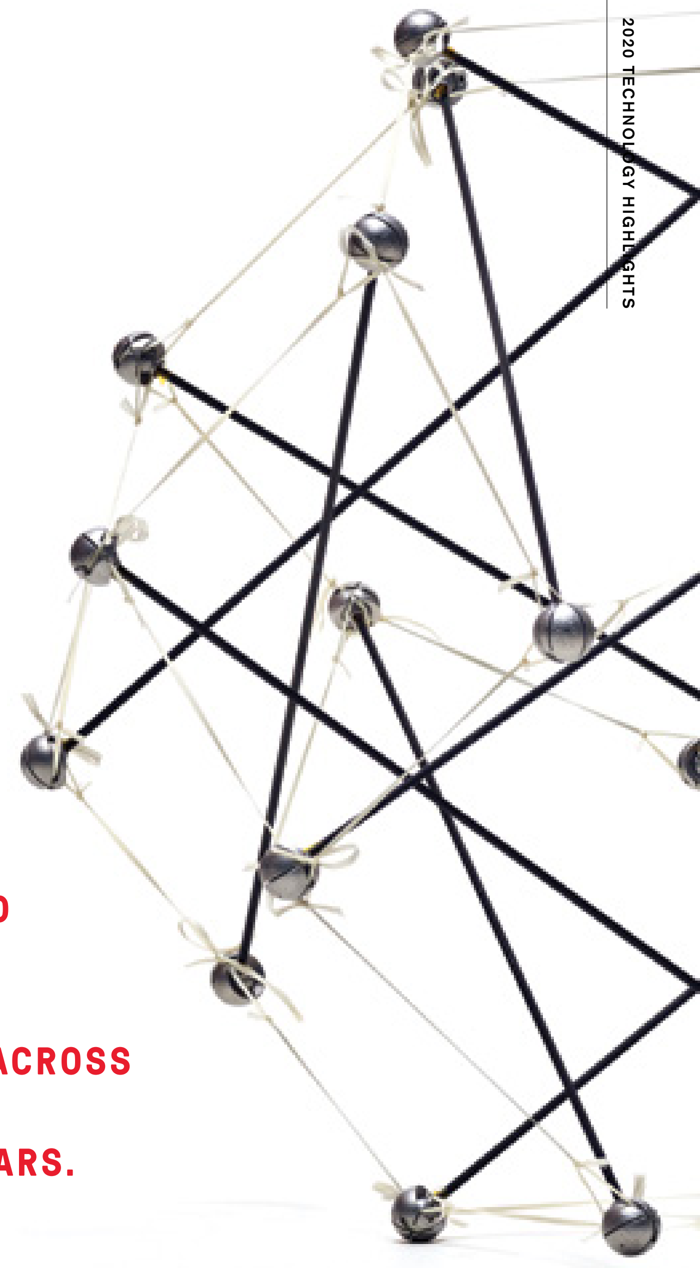
Previous Mars rovers have all been built on the same general design: a monolithic equipment deck atop a body housing electronics, with wheels attached for mobility. For decades, these rovers have executed targeted science missions, continuing to provide the world invaluable science. Now, researchers are interested in new designs to pursue low-cost, distributed, and opportunistic science across larger distances.

The tumbleweed robot is a round, ultralight, and durable system that uses wind to roll across the Mars surface. Previous concepts for spherical rovers have been inflatable. Instead, this design uses a tensegrity structure, composed of bars, cables, and joints. The 30-bar structure has three internal sails. This design maximizes drag and reduces exposure to rocks and other obstacles. The structures are sometimes referred to as “airbags without air” because they distribute forces throughout the entire system once deployed. A payload can be mounted inside the mainly hollow structure to gather data as the robot rolls across the terrain.

This lightweight design can cover much larger distances than heavier, wheeled rovers. Using wind to mobilize, the robot is not dependent on a power supply to continue moving. Further, numerous structures can be deployed to collect spatially distributed data. The tensegrity structure can withstand high impacts and are redundant to member failure, unlike previous inflatable designs. By traversing rough terrain, these robots allow for exploration of previously unreachable areas at low cost. The distributed systems are also robust to single units being lost or stuck.

A series of tests done at the California Institute of Technology’s Lucas Wind Tunnel were used to characterize aerodynamic performance. The tests showed the entire system, including a payload, began to roll between 6.5-10 mph on flat ground. During field-testing with an installed payload, the system successfully rolled uphill on both a dirt road and obstructed desert terrain, freed itself from an obstacle, and became airborne after gaining speed and rolling over an obstacle. Low, inconsistent wind (less than 7 mph) was still able to propel the robot. This design provides a solid foundation for various mission architectures; especially missions built around small, distributed instruments. Planetary exploration applications are not limited to Mars, but could be extended to the Moon, Titan, and many other targets. If wind is not reliable, a modified mobility system could potentially be incorporated to control when or where the system moves.

TENSEGRITY STRUCTURE MAKES THIS ROUND WIND-PROPELLED ROBOT LIGHTWEIGHT AND DURABLE, PERFECT FOR EXPLORING ACROSS THE WIDE DISTANCES OF RUGGED TERRAIN ON MARS.



FLEX TO COMPRESS

09

An international standard

FAST LOSSLESS EXTENDED DATA COMPRESSOR (FLEX) ALLOWS SPACECRAFT TO QUICKLY TRANSMIT VAST AMOUNTS OF HIGH-QUALITY IMAGES.

Left: Calibrated image cube shows how layers of information from different wavelengths of light are combined to create a detailed material map of any given location.

Above: FLEX has flown on two missions so far, top, the Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and, bottom, the Airborne Visible InfraRed Imaging Spectrometer-Next-Generation (AVIRIS-NG).

Imaging satellites collect more than 100 terabytes of data—the equivalent of over 4 years of video–per day. Conventional digital cameras usually only record red, blue, and green light values, but some imaging satellites use hyperspectral sensors to capture data at hundreds of different wavelengths of light across the electromagnetic spectrum. The increasingly comprehensive view of our planet helps with everything from resource tracking to disaster response. All that extra detail results in even higher data volumes, further straining the limited communication channels we use. Fast, high-quality data compression is needed to use the vast amount of valuable information these imaging satellites offer.

The Fast Lossless EXtended data compressor (FLEX) is an algorithm that can compress hyperspectral imagery data without losing any critical data in the process. Implemented on a field-programmable gate array, the algorithm compresses imagery in real time. To compress a layer of data representing an individual wavelength, the algorithm predicts each pixel of the layer based on previously compressed pixels—including those in other layers. This process reduces the amount of data to be transmitted. After transmission, layers are reconstructed with little or no loss of detail. Layers of less importance can be compressed more, while critical layers are prioritized and transmitted without any more data loss than the user specifies—including no loss at all. FLEX is more effective than traditional image compressors, which treat each layer separately. It is also faster and simpler than other methods that make use of the correlation between layers.

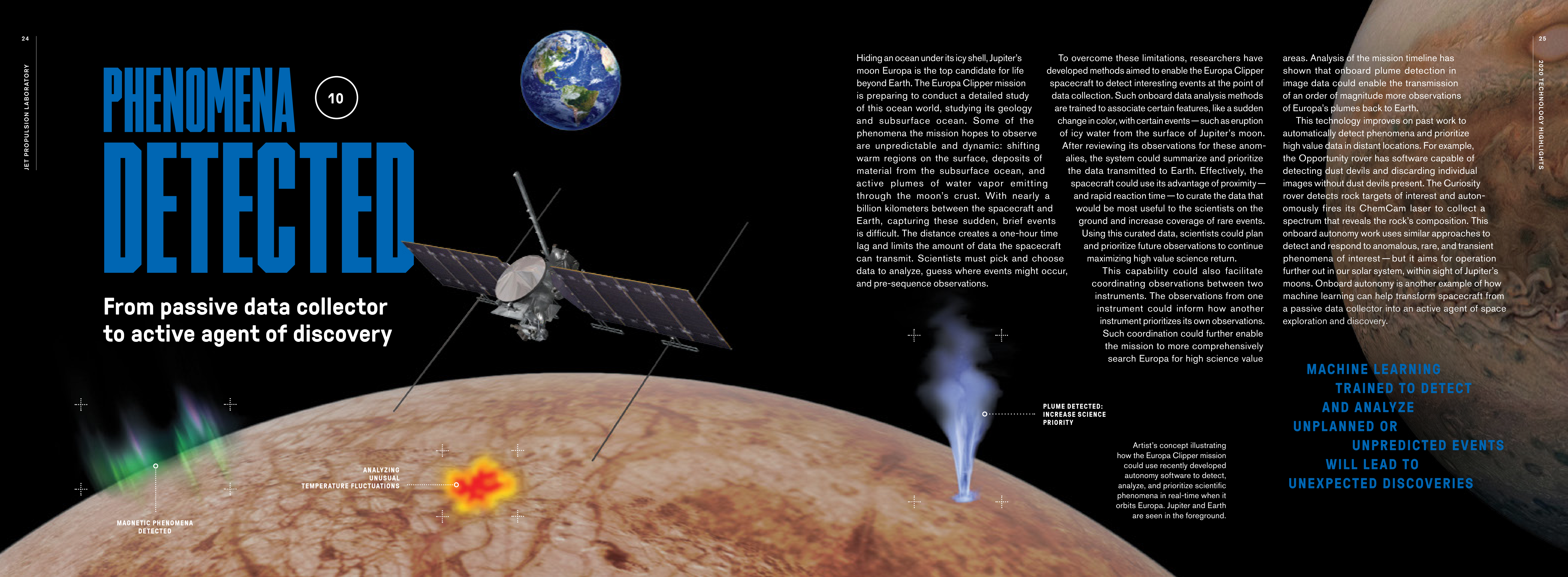
A key enabling technology is a new low complexity "hybrid entropy coder" that adapts to changing prediction accuracy, compressing more predictable data in the image more effectively. Compared to conventional compressors, FLEX requires substantially fewer computational resources. This improved simplicity makes this compressor well suited to the constraints of spacecraft.

The FLEX compressor was deployed on orbit as part of the Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station in July 2018, giving scientists insight into the effects of droughts and heat waves on crop growth. The tool is scheduled to return to the International Space Station to transmit data on atmospheric dust storms to inform climate forecasts as part of the Earth Surface Mineral Dust Source Investigation. Although designed for Earth observation, FLEX could potentially find use in any application that deals with imaging spectrometer data, including agriculture, environmental monitoring, biotechnology, and machine vision, to name just a few. The new algorithm is already an international standard.

PHENOMENA DETECTED

10

From passive data collector to active agent of discovery



Hiding an ocean under its icy shell, Jupiter's moon Europa is the top candidate for life beyond Earth. The Europa Clipper mission is preparing to conduct a detailed study of this ocean world, studying its geology and subsurface ocean. Some of the phenomena the mission hopes to observe are unpredictable and dynamic: shifting warm regions on the surface, deposits of material from the subsurface ocean, and active plumes of water vapor emitting through the moon's crust. With nearly a billion kilometers between the spacecraft and Earth, capturing these sudden, brief events is difficult. The distance creates a one-hour time lag and limits the amount of data the spacecraft can transmit. Scientists must pick and choose data to analyze, guess where events might occur, and pre-sequence observations.

To overcome these limitations, researchers have developed methods aimed to enable the Europa Clipper spacecraft to detect interesting events at the point of data collection. Such onboard data analysis methods are trained to associate certain features, like a sudden change in color, with certain events—such as eruption of icy water from the surface of Jupiter's moon. After reviewing its observations for these anomalies, the system could summarize and prioritize the data transmitted to Earth. Effectively, the spacecraft could use its advantage of proximity—and rapid reaction time—to curate the data that would be most useful to the scientists on the ground and increase coverage of rare events. Using this curated data, scientists could plan and prioritize future observations to continue maximizing high value science return.

This capability could also facilitate coordinating observations between two instruments. The observations from one instrument could inform how another instrument prioritizes its own observations. Such coordination could further enable the mission to more comprehensively search Europa for high science value areas. Analysis of the mission timeline has shown that onboard plume detection in image data could enable the transmission of an order of magnitude more observations of Europa's plumes back to Earth.

This technology improves on past work to automatically detect phenomena and prioritize high value data in distant locations. For example, the Opportunity rover has software capable of detecting dust devils and discarding individual images without dust devils present. The Curiosity rover detects rock targets of interest and autonomously fires its ChemCam laser to collect a spectrum that reveals the rock's composition. This onboard autonomy work uses similar approaches to detect and respond to anomalous, rare, and transient phenomena of interest—but it aims for operation further out in our solar system, within sight of Jupiter's moons. Onboard autonomy is another example of how machine learning can help transform spacecraft from a passive data collector into an active agent of space exploration and discovery.

MACHINE LEARNING TRAINED TO DETECT AND ANALYZE UNPLANNED OR UNPREDICTED EVENTS WILL LEAD TO UNEXPECTED DISCOVERIES

Artist's concept illustrating how the Europa Clipper mission could use recently developed autonomy software to detect, analyze, and prioritize scientific phenomena in real-time when it orbits Europa. Jupiter and Earth are seen in the foreground.

Deployable Antarctic Sheet Exploration Rovers (DASHER) during field tests in the Mojave. Each DASHER would be equipped with its own compact radar, based on a printable antenna design.

Synchronized roving

11 ON DASHER!

"Talent wins games, but teamwork and intelligence wins championships," according to basketball champion Michael Jordan. The same proves true in space exploration. It takes a lot of people to land something on Mars—more if it moves on the surface or flies. Right now, many teams operate several missions across the solar system. What if there could be a team on the other side of the operator's console?

Deployable Antarctic Sheet Exploration Rovers (DASHER) are a team of radar-equipped rovers designed to map the bottom of ice sheets down to the centimeter. In this mission concept, the collection of robots does not just cooperate by dividing the task of scanning surface area cooperatively and autonomously. They coordinate their movement as well as radar to create a synthetic aperture; many radars precisely coordinated can act like one much larger radar. They may steal the show, but the robots are just a (quite sophisticated) vehicle for a new system that relies on a few technical innovations. The need for sub-nanosecond precision required writing new protocols, and a newradar was developed as well. This leap in capability is enabled by software-defined radar technology combined with autonomous robotic technology.

MOBILE RADAR-EQUIPPED ROBOTS COOPERATE TO RAPIDLY IMAGE SEASONAL CHANGES OF THE BOTTOM OF ICE SHEETS.

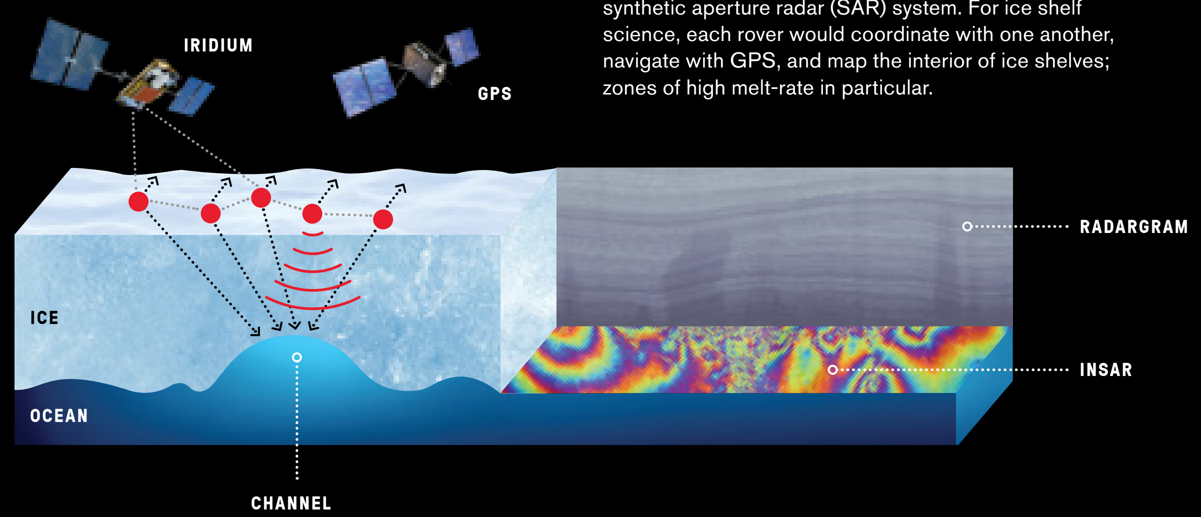


Diagram illustrating the concept of operations for DASHER, a mobile, multi-static ground-penetrating synthetic aperture radar (SAR) system. For ice shelf science, each rover would coordinate with one another, navigate with GPS, and map the interior of ice shelves; zones of high melt-rate in particular.

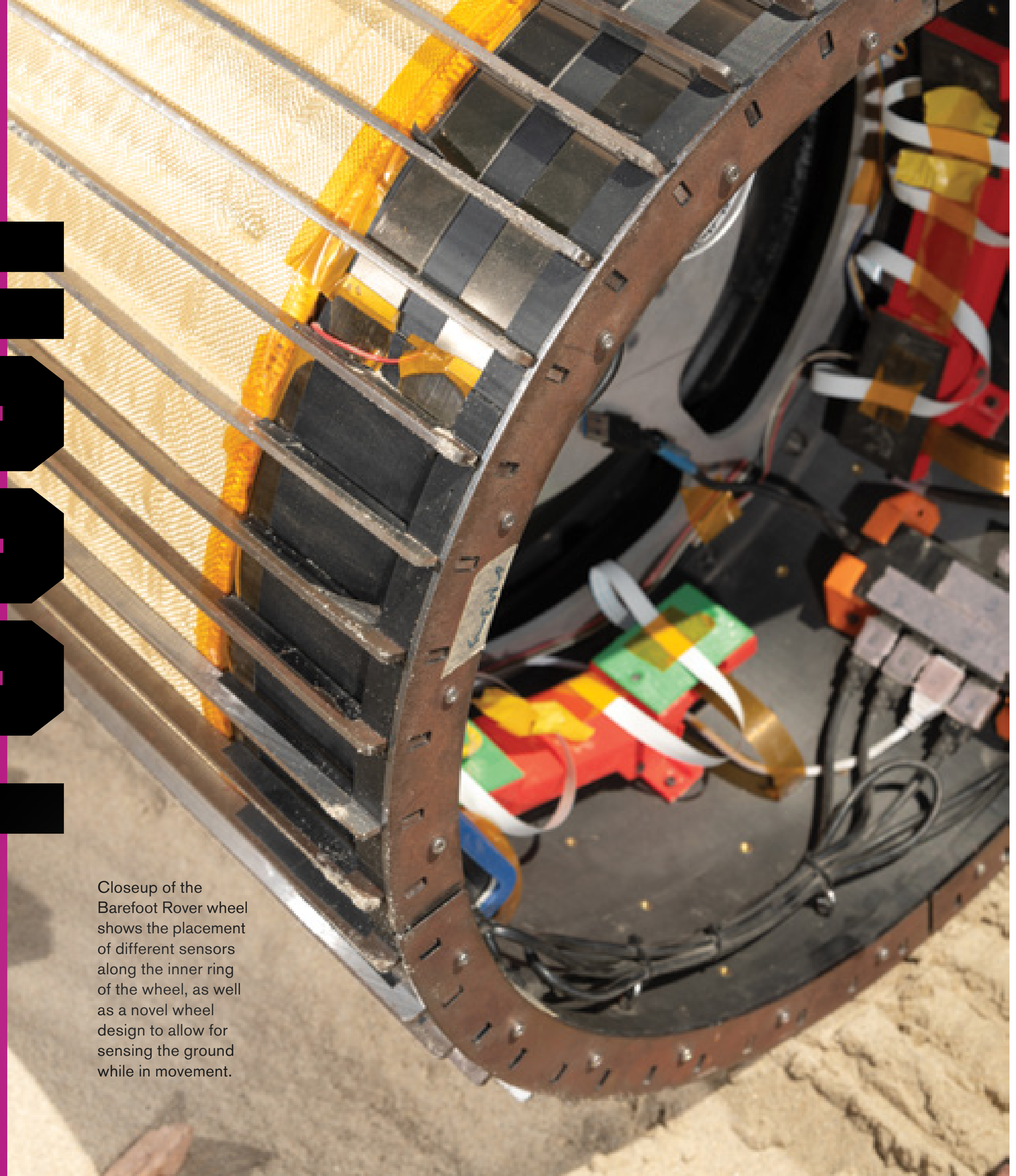
DASHER have been designed with Ground Penetrating Synthetic Aperture Radar to map changes in the bottom of kilometer thick ice shelves: massive floating extensions of polar ice sheets that surround the Antarctic and are subject to ocean melting from below. These ice shelves "buttress" or regulate the speed at which grounded ice is able to flow into the ocean and impart the largest uncertainty, relative to any other mechanism, on the future projections of ice sheet and sea level change. Without greatly advancing our understanding of the processes by which heat is transferred from the ocean to the ice shelves, little progress can be made in reducing uncertainties in sea level projections. DASHER can not only get centimeter precision, far superior to other platforms, but much more quickly too: days to weeks instead of weeks to months.

This technology has wider applications on Earth, and very direct application to our exploration of other planets. DASHER can facilitate future fleets of robots on Mars or constellations on Venus.

Feeling our way on other worlds

TOUCH AND GO

12



Closeup of the Barefoot Rover wheel shows the placement of different sensors along the inner ring of the wheel, as well as a novel wheel design to allow for sensing the ground while in movement.

Imagine you are walking onto the beach: your steps slide on the loose, soft sand of the dunes. Heading to the ocean, the ground becomes hard and coarse. Once you reach the water, you let your feet slowly sink into the wet, shifting sand. Now, imagine you did not have your sense of touch to guide your steps to the ocean. How safely, and quickly, could you have reached the water?

Currently, rovers rely on sight alone to navigate. They send pictures of the terrain to ground operators, who analyze the images to determine the best path forward. Visuals provide incomplete information, requiring operators to guess terrain features. This method also requires manual, post-hoc analysis that slows the rover's progress and limits its ability to navigate independently. In person, these operators would also use their sense of touch to analyze terrain—so why don't rovers?

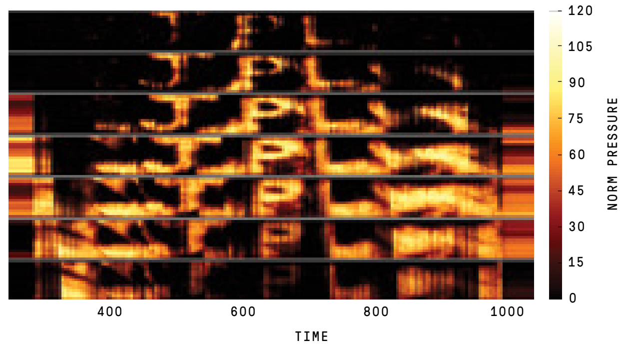
WHEELS EQUIPPED WITH SENSORS AND ARTIFICIAL INTELLIGENCE ENABLE ROVERS TO RECOGNIZE TERRAIN WITH UNKNOWN CHARACTERISTICS

Barefoot Rover is a wheel concept that enables the rover to "feel" the terrain it's traveling across. Using a 2D pressure grid of sensors and an electrochemical sensor, the wheel senses features of the terrain. With machine learning, it analyzes the interaction between the wheel and the surface. The rover can assess metrics including slip and sink rates, balance, sharpness, surface hydration, texture, and terrain patterns. Using these metrics, a rover could recognize loose sand and halt a drive, or feel rock and better distribute power to the wheels.

To develop this capability, Barefoot Rover has undergone over a thousand runs over different materials, from soft sand to coarse rocks. These runs provide sensor data to train machine learning models, which teach the rover to identify the terrain.

All exploration or mapping missions benefit from the greater safety, precision, agility, and autonomy that Barefoot Rover offers. The wheels also provide opportunistic science to rover missions, extracting information such as soil moisture. Expeditions to harsh environments on Earth, such as climatology studies in Antarctica, also benefit from this capability. Disaster response and rescue could also one day benefit from robots that feel their way through dangerous terrain, or to avoid hurting people. Barefoot Rover brings humans one step closer to touching the surface of distant, uncharted destinations.

The Barefoot Rover testbed was utilized to train machine learning algorithms on different materials, surface conditions and material hydrations. Here, Jack Lightholder poses with the testbed.



Graph showing the Barefoot Rover wheel identifying "JPL" written in the sand underneath it.

Top and Bottom Left:
The Ocean Worlds Life Surveyor team is shown here working in 2019.

MOTION PICTURES

13

Looking for life wisely

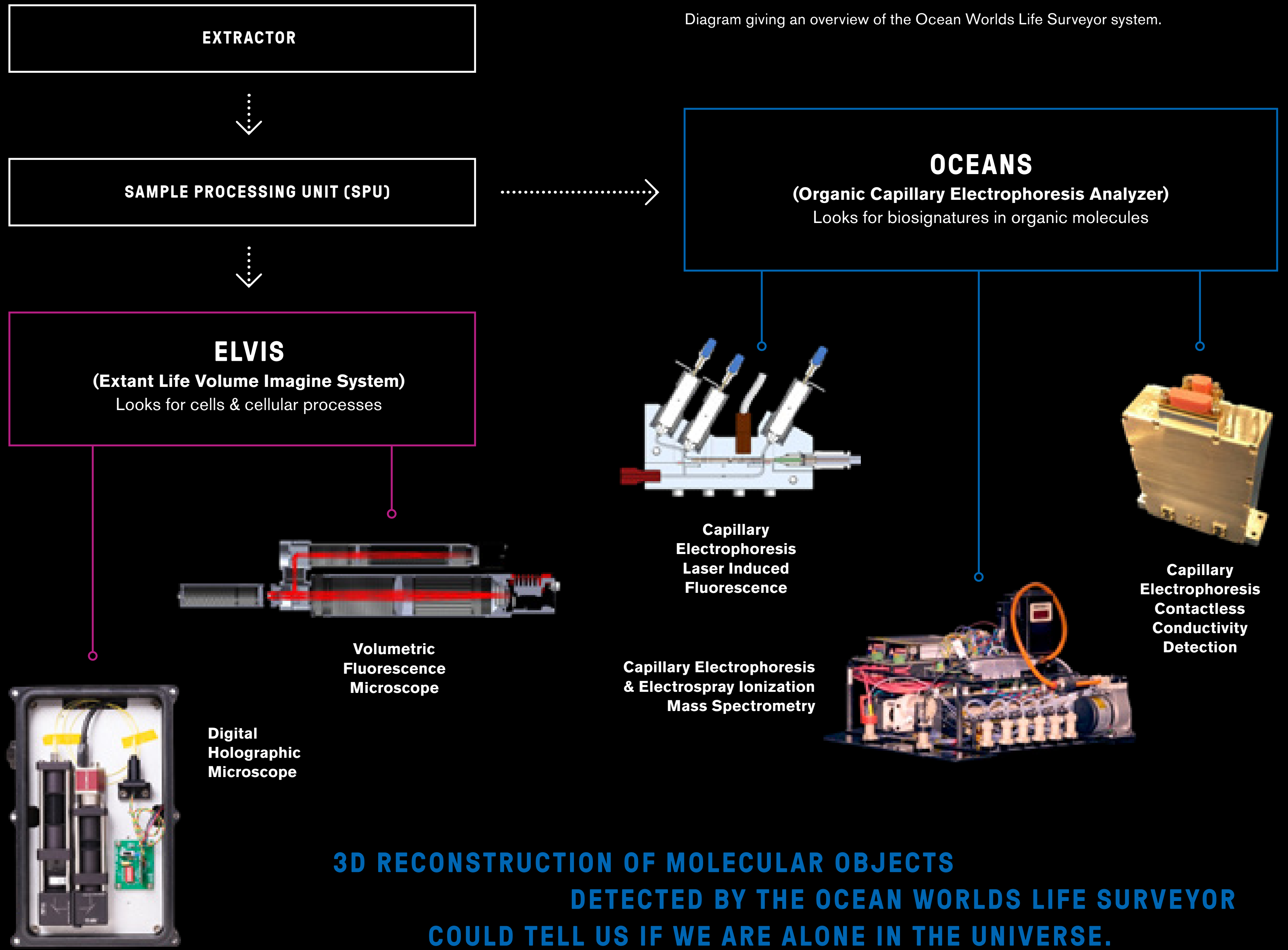
Are we alone in the universe? The answer could be in our own solar system. To conduct this search, scientists are "following the water," investigating the discoveries of water on Mars, Europa, and Enceladus. Now, the challenge is no longer where to look but what to look for and how. A capability is needed that can both detect organisms and determine evidence of current or past life—all while operating autonomously in space.

The Ocean Worlds Life Surveyor (OWLS) is the first life detection instrument suite for future missions to ocean worlds. The suite, designed from scratch, presents the most complete set of life detection tests on a single sample. OWLS searches for life comprehensively at the molecular and cellular levels: three detection methods perform molecular analyses, searching for amino acids, charged species, and collections of organic molecules. These detection methods are combined with two microscopic imaging methods. One of the imagers is the Digital Holographic Microscope (DHM), which enables the surveyor to track the motion of microorganisms.The other is the Volumetric Fluorescence Microscope (VFM), which can detect chemical features of microscopic life.

The DHM uses laser light to capture 3D images of the sample object. A laser illuminates the sample, transmitting light through both the sample and an empty reference volume to the detector. This scattered light reveals detailed information about the object. A computer uses this information to reconstruct a 3D image of the microorganism. This process offers at least 50 times more depth of field than a conventional microscope without any mechanical focus element. With this added depth, DHM can track the tiniest of motions, detecting particles down to a tenth of a micron. A machine learning algorithm then analyzes the data for motion patterns that indicate possible life. Sampling Newport ocean water, OWLS detected 6–15 microorganisms moving in patterns that are indicative of life.

Currently in prototype phase, the system is close to the limits of detection possible with each of the instruments. Future testing in the High Arctic will validate the technology for potential astrobiology missions to ocean worlds such as Enceladus and Europa. OWLS will be customizable to analyze samples on Europa, Enceladus, or even an asteroid. Although designed for spaceflight, the customizable suite could also be used for applications here on Earth. Ecology studies could use the instrument to monitor the chemistry and health of Earth's waters. The instrument could also support medical diagnostics, detecting bacteria at very low concentrations.

Diagram giving an overview of the Ocean Worlds Life Surveyor system.



3D RECONSTRUCTION OF MOLECULAR OBJECTS DETECTED BY THE OCEAN WORLDS LIFE SURVEYOR COULD TELL US IF WE ARE ALONE IN THE UNIVERSE.

FINE LINES

14

Spectral rulers to measure the stars—and find Earth-like planets

Astronomers believe there is at least one exoplanet per star in our galaxy—that's billions of planets in the Milky Way alone. Most of the over 4,000 exoplanets discovered are ice or gas giants like Neptune or Jupiter. Their large size and weight make them easier to detect. Neptune, a smaller giant, is 17 times as massive as Earth. Earth-like exoplanets capable of harboring life as we know it are small, rocky and in the 'habitable zone,' where water can exist as a liquid. Currently used technology is not sensitive enough to detect the kinds of planets we would actually want to live on.

Arrays of high-Q ring resonators on silicon used for frequency microcomb generation.

Most exoplanet detection methods rely on spectrometer technology. Spectrometers detect and measure different kinds of light, and improving their sensitivity is key to finding smaller exoplanets, especially around brighter, Sun-like stars. Laser Frequency Combs (LFC) can help achieve this precision. They provide the needed spectral references, like a ruler, but for measuring light. However, LFCs require complex and sophisticated hardware, like large instruments that require multiple stages of filtering.

Engineers developed a new chip-based "soliton microresonator-based comb," or microcomb. In addition to being tiny, microcombs have line spacing that is ideally suited for astronomical calibration—eliminating the need for filtering. Previously, microcombs lacked the stability needed to work as frequency combs. Soliton formation, a technology also seen in optical fiber, ensures these microcombs have highly stable mode locking and reproducible spectral envelopes—key to accurately and efficiently detecting exoplanets.

The current prototype system occupies approximately 1.3 m in a standard instrument rack. When calibrating the near infrared spectrograph at the W.M. Keck observatory, this soliton microcomb enabled precision at the few m/s level (about 0.1 m is needed to detect Earth-like planets). This technology is applicable to other types of spectroscopy, but LFCs are also central a new generation of optical clocks, 100 times more accurate than today's state of the art.

The system could ultimately come in a chip-integrated package—measured in centimeters. Such dramatic reduction in size, weight, and power consumption could give this laboratory capability to miniaturized explorers, enabling constellations of small satellites, or a fleet of mini-robotic explorers on another world.

MINIATURIZED, CHIP-BASED FREQUENCY COMBS, BUILT WITH ADVANCED MANUFACTURING TECHNIQUES, CAN PRECISELY CALIBRATE THE SEARCH FOR EARTH-LIKE PLANETS.

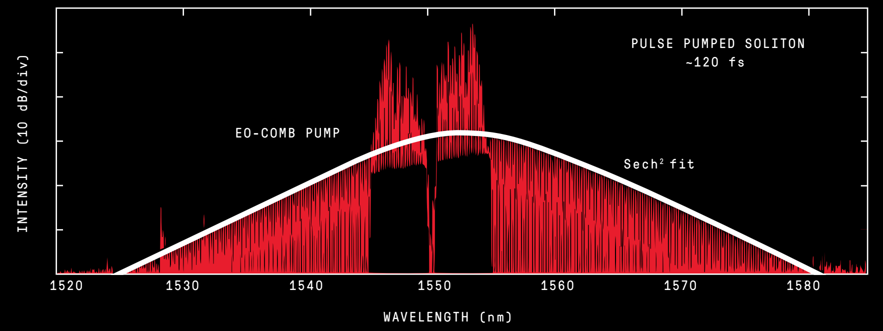


Figure showing a broad spectrum of uniformly spaced frequency comb lines generated by pulse-pumping a soliton microcomb.

IN[VENT]ING LIFE

15

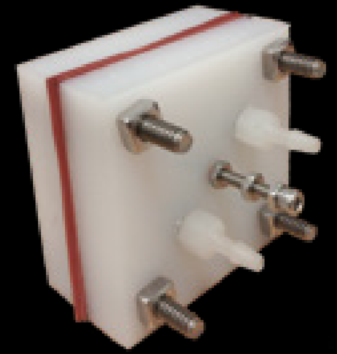
Vents on ocean worlds could be fueling life

The Membrane Electrode Assembly (MEA) pictured here is made with iron sulfide paint, because it is analogous to hydrothermal vent precipitates that would have existed on early Earth or ocean worlds.

Scientists believe life will be discovered beyond Earth in our lifetime. The icy moons Enceladus and Europa are thought to be ocean worlds underneath, with hydrothermal vents, where water and rock interact at high temperatures. On Earth, such vents nurture rich ecosystems and are known to fuel life. Some also theorize they are the origin of life we know. By studying the chemical reactions produced within possible vents on ocean worlds, scientists could gain insight into the energy landscape available to harbor or sustain life. That in turn could help refine the design of instruments for future missions to find life.

Since inception in 2019, there have been three iterations of this scientific fuel cell (below). The most recent work has adapted this technology to additional catalysts for ocean worlds.

VERSION 3



VERSION 2

VERSION 1

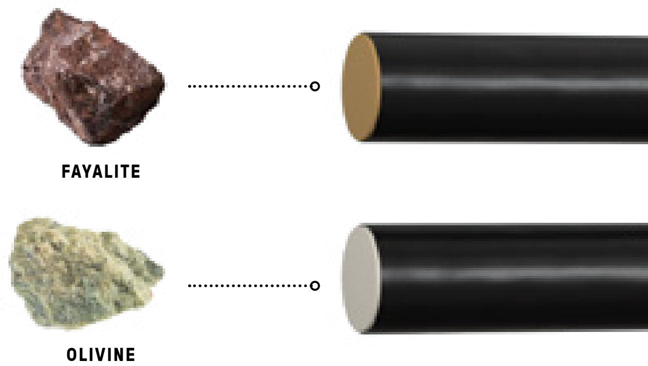
ADVANCED MANUFACTURING TECHNIQUES ENABLE CUSTOM TESTBEDS THAT CAN SIMULATE THE CHEMISTRY OF UNDERWATER VENTS AND THE KINDS OF ORGANISMS THAT ENERGY COULD SUSTAIN.

Simulating these reactions is a challenge, as chemical gradients (each gradient having different concentrations of ions or molecules) usually dissipate before they can be studied. New "planetary test beds" use fuel cell technology to simulate these chemical reactions in an analogous, lab-created environment. Fuel cells enforce chemical gradients by separating reactions (oxidation and reduction) with an "ion exchange membrane." This technology allows gradients to be studied independently and precisely, but still with the accuracy required to achieve realistic, comparable results.

Fuel cells are usually optimized for energy generation. To use them to simulate natural environments instead, technologists created a custom fuel cell housing for that purpose. They also developed a new "geo-electrode" fabrication technique to allow the incorporation of rocks and minerals into fuel cell membrane electrode assemblies, instead of the usual catalysts such as platinum or carbon.

Scientists can use these test beds to reproduce and analyze energy found in water and rocks on other planetary bodies. This analysis helps us characterize the habitability of seafloor systems on ocean worlds. For example, to study life on Enceladus, scientists could combine minerals like those found in its subsea with components of interest to that environment. The reactions of the system could then narrow down the most likely metabolisms to target in the search for life on that ocean world.

This technology can also be used to create new, more accurate simulations of other astrobiology-relevant systems we cannot study directly. Scientists could simulate hydrothermal vents on the Earth 4 billion years ago when life emerged, subsurface and early Mars, and Earth's modern deep sea. The methods pioneered for this test bed can be diversified to a wide range of planetary relevant minerals that may affect the energy for life on other worlds. The test bed could also be adapted to include carbon reactions, helping us learn about the origin of life on our own planet.



Ocean worlds relevant geological samples are used to coat the electrodes in a mineral paint (here, olivine and fayalite). Optimizing fuel cells for science requires different materials and processes than optimizing them for energy generation.

VITAL SIGNS

16

A race to breathe life into COVID-19 patients

6 of the 50 engineers that developed the Ventilator Intervention Technology Accessible Locally (VITAL) pose with their prototype. They were able to design, develop, and receive FDA approval in under 40 days.

In early March of 2020, 50 engineers stepped away from their rovers and satellites to work on a very different kind of technology: ventilators. With the COVID-19 pandemic mounting across the globe, ventilator shortages have been a leading concern. Estimates for the number of ventilators the United States might need ranged from several hundred thousand to as many as a million—far more than the 160,000 in hospitals.

The team dedicated themselves to designing and developing an affordable, mass-manufactured ventilator tailored to treat COVID-19 patients. Working 14-hour days, 7 days a week, they succeeded: a new ventilator called VITAL (Ventilator Intervention Technology Accessible Locally) was completed in just 37 days. This feat is comparable to completing an entire flight subsystem, from formulation to pre-launch assembly and testing, in just five weeks.

The ventilator delivers the specific high-pressure oxygen flows needed to sustain COVID-19 patients, whose lungs are severely weakened by the virus. The device is faster to build and easier to maintain than a traditional ventilator. The simpler design uses one-seventh the parts of standard ventilators. VITAL can be mass-manufactured, using parts already available for industrial uses. The engineers were careful to avoid parts already used in hospital ventilators, to ensure manufacturing did not block production of other ventilators.

On April 21, 2020, VITAL underwent testing at the Icahn School of Medicine on Mount Sinai in New York City, using a high fidelity human patient simulator. The prototype received an Emergency Use Authorization from the Food and Drug Administration on April 30. The engineers have now passed the baton to the manufacturing community. Caltech offered the design for licensing on a royalty-free basis. Over a hundred manufacturers applied in the first round for a free license to build the JPL-designed ventilator. Nine U.S. manufacturers across the country and 19 international manufacturers across 6 continents have been selected from that round, and more are expected.

This new device will not replace current hospital ventilators, which can last years and are built to address a broader range of medical issues. Instead, VITAL lasts three or four months, treating COVID-19 specifically. It offers a cheaper, more accessible option for COVID-19 patients while freeing up more powerful hospital ventilators for the most severe cases. The user-friendly, flexible design means this ventilator can be modified for use in field hospitals being set up in convention centers, hotels, and other high-capacity facilities around the globe.

VITAL IS A NEW VENTILATOR MADE FOR COVID-19 PATIENTS. IT WAS DESIGNED IN 37 DAYS, DOES NOT DISRUPT INDUSTRIAL VENTILATOR PRODUCTION, AND IS ALREADY LICENSED TO 28 MANUFACTURERS AND COUNTING.

Closeup of Ventilator Intervention Technology Accessible Locally (VITAL), which is specifically designed for COVID-19 patients without disrupting existing ventilator production supply chains.

SMART SUB

17

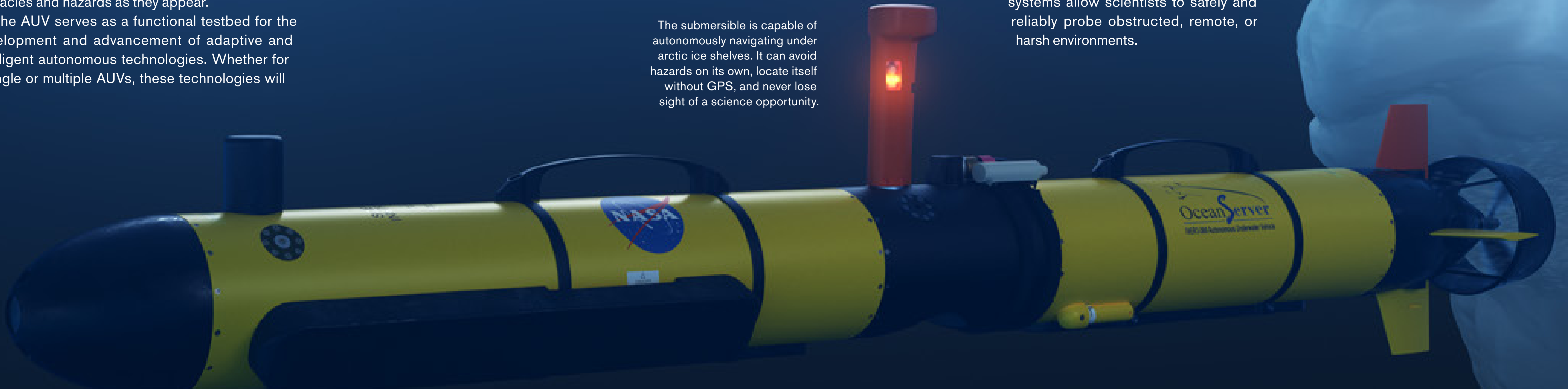
Autonomy is key to underwater exploration on any planet

Exploration of the oceans on other planets will require autonomous underwater vehicles (AUV). There is no other way to give these missions a chance with current technology. Avoiding hazards and detecting potential signs of life will need to be done without a person, not to mention the kilometers of ice and intense radiation on Europa, for example. Indeed, current technology needs to be pushed to achieve this goal. Few ocean observations have been made inside ice-shelf cavities. These harsh, remote environments are difficult to access with traditional observational platforms. Developing this technology on Earth is both bringing in new science and getting us closer to a truly autonomous mission under the surface of a planetary ocean.

Intelligent, adaptive, onboard autonomy software allows an AUV to navigate the unknown GPS-denied water environment. This software extends standard surface planning to a 3D environment, enabling the system to orient itself and map a path forward at appropriate depth, heading and speed based on the environment, including avoiding obstacles and hazards as they appear.

The AUV serves as a functional testbed for the development and advancement of adaptive and intelligent autonomous technologies. Whether for a single or multiple AUVs, these technologies will increase the science return for exploration of ocean worlds. This testbed AUV has the capability for integration of additional sensors in its extended payload bay, for example a compatible acoustic modem for communicating with the Buoyant Rover for Under-Ice Exploration (BRUIE) was tested for data exchange and positioning. Future under-ice enabling technologies could include the AUV identifying potential under-ice landing sites (e.g. based on characteristics such as slope, roughness) for deployment of a distributed set of instruments that measure ice-melt rates (Icepods), all without extensive drilling. Additionally, the AUV can be tasked to perform science data collection missions for sonar mapping and/or environmental monitoring with its onboard sensor suite.

The onboard autonomy software supports applications and missions for Earth Science, like mapping of coral reefs based on fusion of data, Planetary Science, Naval research, and even commercial applications like inspecting the underwater cables that connect the world. Onboard sensing, reasoning and decision-making, detection and tracking features of interest, and adaptive sampling are some of the demonstrated autonomous capabilities needed for missions on ocean worlds, like Europa or Enceladus. Autonomous systems allow scientists to safely and reliably probe obstructed, remote, or harsh environments.



The submersible is capable of autonomously navigating under arctic ice shelves. It can avoid hazards on its own, locate itself without GPS, and never lose sight of a science opportunity.

AUTONOMOUS UNDERWATER VEHICLE (AUV) IS ABLE TO LOCALIZE ITSELF WITH SONAR, PLAN ITS PATH AROUND HAZARDS, AND PERFORM OPPORTUNISTIC SCIENCE.

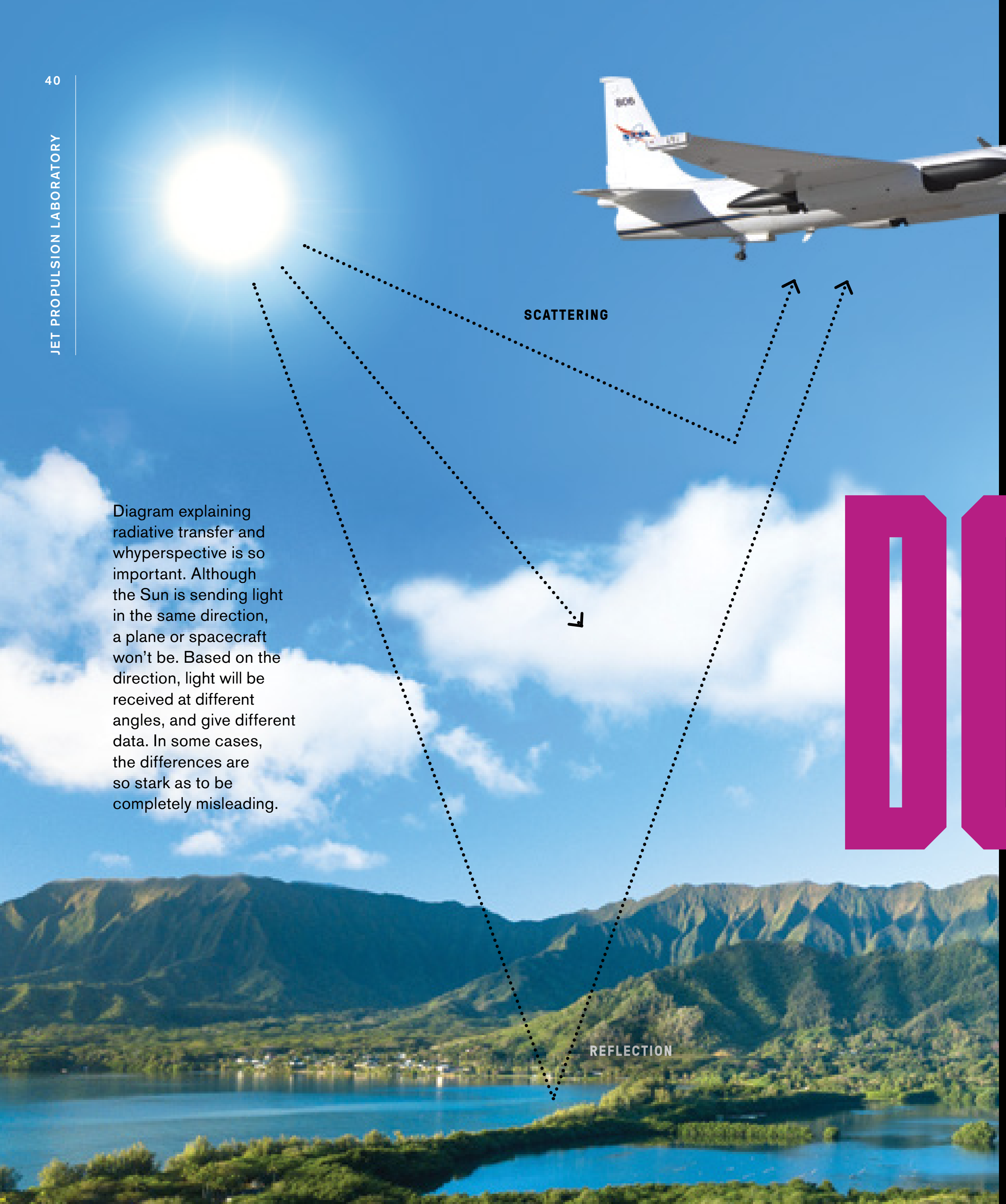


Diagram explaining radiative transfer and whyperspective is so important. Although the Sun is sending light in the same direction, a plane or spacecraft won't be. Based on the direction, light will be received at different angles, and give different data. In some cases, the differences are so stark as to be completely misleading.

18

SEEING DOUBLE

Faster models, smarter science

NEURAL NETWORK REGRESSION MODELING CAN BE TRAINED TO SOLVE COMPUTATIONALLY INTENSIVE PROBLEMS, LIKE RADIATIVE TRANSFER MODELING.

Perspective can radically alter just about everything; the right perspective can make tough problems easy. Even the light we see depends on the angle we observe, the location of the source, and the materials around us. Light is absorbed by gases like water vapor, reflected by the surface, and scattered by particles like dust as it passes through the different parts of the atmosphere. The processes of absorption, emission, and scattering of radiation—including the visible light that human eyes can sense—within the atmosphere critically impact our planet's climate. Measurements of light can also be a powerful tool to understand the surface—to monitor biodiversity, water quality, or the health of our forests and farms.

Scientists studying our planet can use the full spectrum of light, including infrared wavelengths that our eyes cannot see, to measure subtle features of the Earth's surface. The absorption of light at different wavelengths can reveal the composition of a forest canopy or the grain sizes in a snowdrift. Even the kind of visible light photography we are all familiar with holds great scientific value when acquired at the right angle. However, measurements of Earth's surface are always affected by the way light interacts with the atmosphere. These differences can be so stark as to make the same picture of the same bay look like it is teeming with life, or completely dead. Traditionally, removing atmospheric interference requires complex mathematical calculations that adjust the image after the fact, known as numerical radiative transfer (RT) models. RT models enable scientists to estimate atmospheric interference and remove it from the observation. However, these models are computationally intensive; their accuracy has traditionally been limited by the computing power available.

Neural Network RT applies artificial intelligence to the RT problem. A neural network is trained to emulate complex atmospheric calculations using machine learning methods. The system learns to replicate the output of a traditional RT program, in a tiny fraction of the time. Neural Network RT can improve the speed of RT calculations by factors of 100 or more. Such speed improvements will be critical for global spectroscopic mapping, such as the anticipated Surface Biology and Geology (SBG) investigation. Neural Network RT may help us keep pace with the flood of observations.

In addition to surface measurements, RT models are important for nearly any study of Earth's atmosphere, including measurements of temperature and humidity. These in turn feed our weather prediction and climate models to find the early signs of a new hurricane or to predict climate change over time. More importantly, the demonstration of machine learning to efficiently and accurately reproduce the results of complex numerical models will be a game changer for scientific exploration.

Images of Kaneohe Bay, Hawaii above show how important radiative transfer models are to scientific observations. In the top image, the sharp contrast in color down the middle suggests half of the bay is teeming with life, while the other half appears lifeless. The bottom image gives us the true view of what's going on below, after using the Neural Network Radiative Transfer algorithm.

Map illustrating a very small sample of incoming and outgoing network traffic globally.

19 DATA PATROL

Hackers are fast, but AI is smart

Cyber-attacks happen every 39 seconds in the United States, with the average cost of a data breach estimated to exceed $150 million in 2020. These attacks are committed by other governments for espionage, as well as rogue organizations and individual hackers for sale. Guarding valuable, sensitive information from these continual, unpredictable attacks requires constant vigilance. Cyber analysts must frequently review network activity to identify potential threats before they can cause damage. Typically, cyber analysts rely on manual approaches to scan and analyze the network. Given how enormous a typical network is, this process is time-consuming, prone to errors, and often cannot detect attacks until after they have concluded. As more of our lives rely on these virtual networks, better cyber-defenses are a must have.

COCKATOO USES MACHINE LEARNING TO GIVE CYBERSECURITY SPECIALISTS THE EDGE IN THE SECOND-TO-SECOND BATTLE OVER DATA NETWORKS.

Diagram showing how Cockatoo scans dense network traffic data for anomalies. These anomalies can also indicate when a cyberattack is occurring in near-real-time.

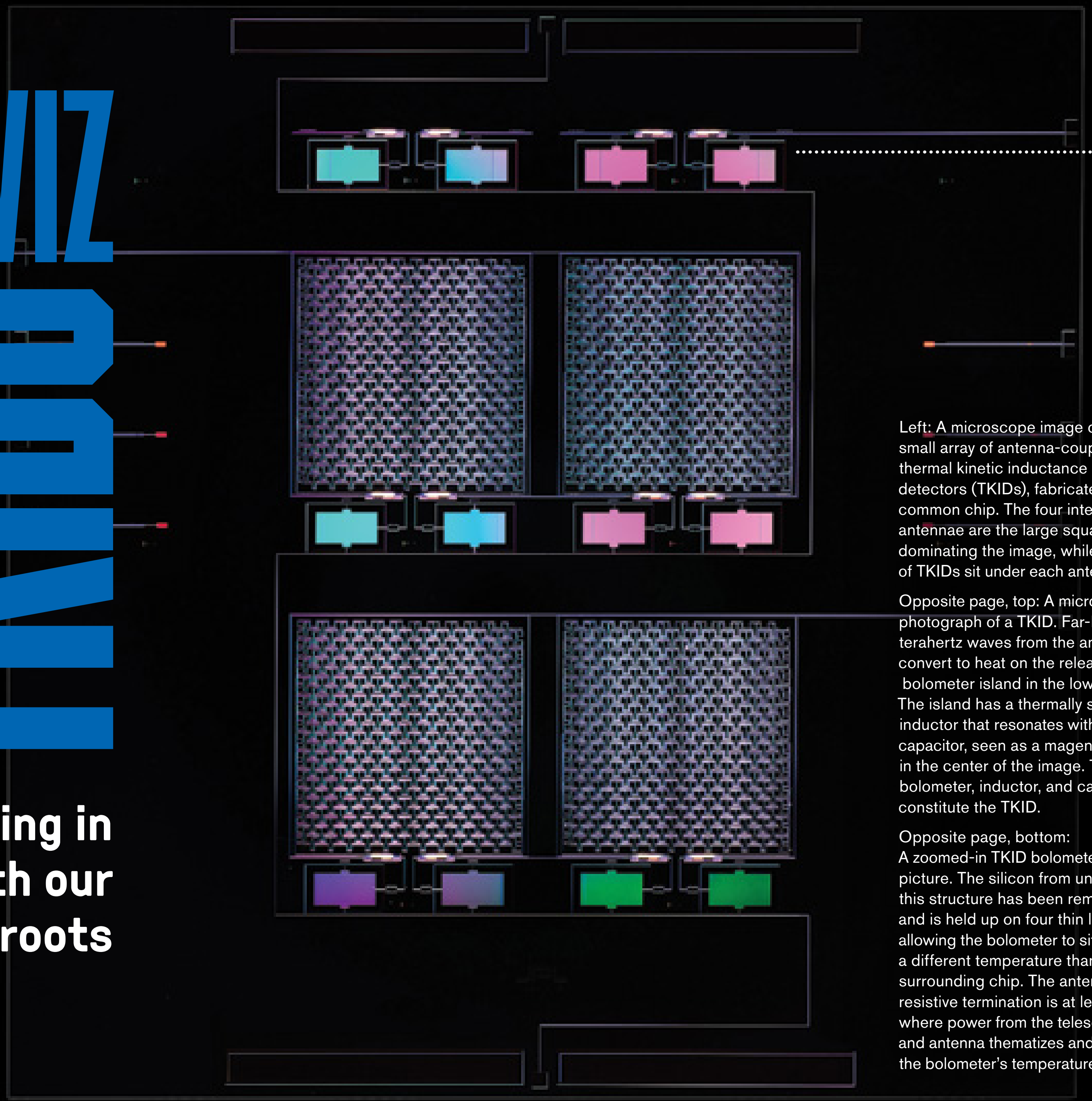
Cockatoo is an AI algorithm that detects cyber threats by monitoring network traffic for unusual activity. Cockatoo leverages unsupervised machine learning techniques to learn the normal user activity behavior on server networks. Most machine learning approaches use supervised learning, where the algorithm learns from a relatively large, well understood, labeled dataset. However, it is often difficult to tell if cybersecurity data is dangerous or safe even after an attack is complete—making supervised machine learning ineffective. With unsupervised learning, Cockatoo can identify patterns independently, catching anomalies and intruders while an attack is happening. This is the only way now known to detect attacks in real time in very large networks with huge flows of unlabeled and encrypted data. Autonomous capabilities like this will completely change the way we defend ourselves from increasingly malicious hackers and spies.

Technology like Cockatoo is key to thriving in an increasingly connected world, and as we rely on software to handle more complex and critical tasks. These techniques have already proven their worth in practice and are being integrated into existing systems. Cyber analysts now have a tool that monitors networks as fast as the Internet moves, and will alert them to any new danger. The same technology can also be applied to science exploration missions for "fault detection, isolation, and recovery," or monitoring the health of space systems onboard and alerting mission operators of any anomalies that should be addressed before a system fails.

20

TKIDS WIZ

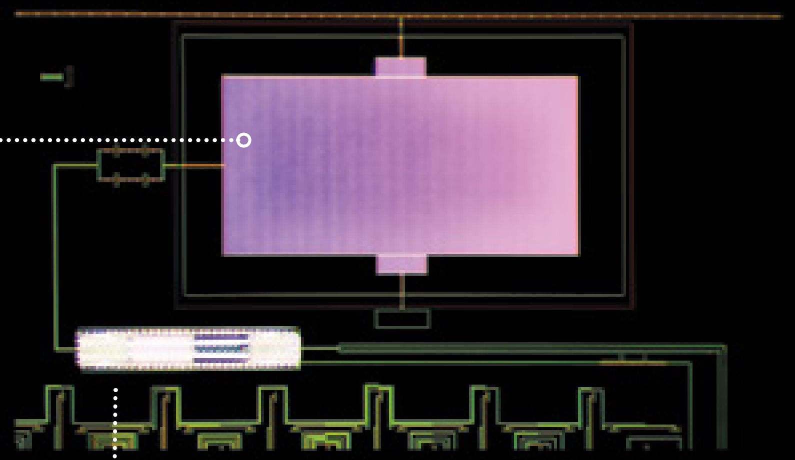
Getting in touch with our cosmic roots



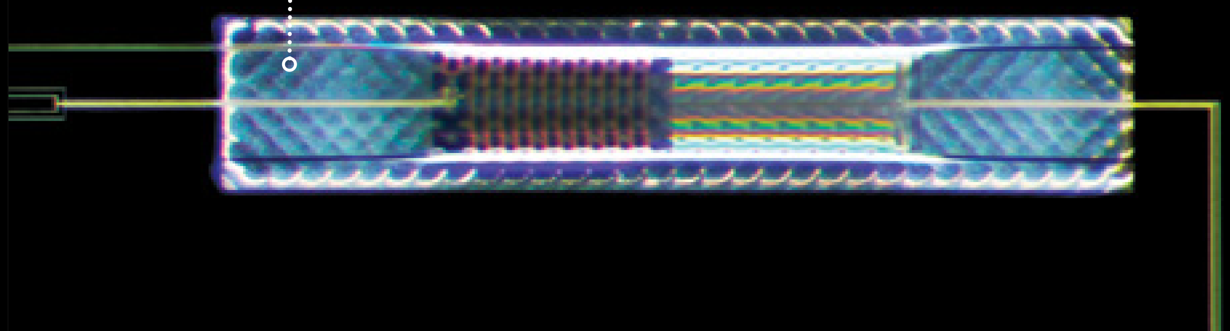
Left: A microscope image of a small array of antenna-coupled thermal kinetic inductance detectors (TKIDs), fabricated on a common chip. The four integrated antennae are the large squares dominating the image, while pairs of TKIDs sit under each antenna.

Opposite page, top: A microscope photograph of a TKID. Far-IR and terahertz waves from the antenna convert to heat on the released bolometer island in the lower left. The island has a thermally sensitive inductor that resonates with the capacitor, seen as a magenta block in the center of the image. The bolometer, inductor, and capacitor constitute the TKID.

Opposite page, bottom: A zoomed-in TKID bolometer picture. The silicon from under this structure has been removed, and is held up on four thin legs, allowing the bolometer to sit at a different temperature than the surrounding chip. The antenna's resistive termination is at left, where power from the telescope and antenna thematizes and alters the bolometer's temperature.



THERMAL KINETIC INDUCTANCE DETECTORS WERE ONCE LIMITED TO LOW FREQUENCIES, BUT ADVANCED MANUFACTURING TECHNIQUES ALLOW TKIDS TO OPERATE AT MUCH HIGHER FREQUENCIES, MUCH MORE RELIABLY.



There is a faint, constant radiation coming from every direction: the cosmic microwave background (CMB). CMB is evidence for the Big Bang theory of our universe's origin, and astronomers have been investigating the phenomena ever since its discovery in 1964. Because CMB is so faint, however, it can be drowned out by any stray signals, and telescopes targeting it are often placed in remote locations, such as the South Pole.

Thermal Kinetic Inductance Detectors (TKIDs) are a new type of sensor designed to detect millimeter-wave, submillimeter wave, and infrared radiation. These bolometers, or heat-energy detectors absorb energy on to a membrane that causes the sensor's temperature to change. Each sensor's data is recorded, and then transmitted along a common line to a computer, where it is interpreted. By coupling several hundred sensors to a common line integrated with the detector array, this approach greatly reduces integration complexity and risk of malfunction.

Previously, TKIDs have been used for X-ray detection and explored for use as near-infrared sensors. However, past research suggested that the suspension membrane would introduce excess noise and render these devices insensitive to longer wavelengths. To make TKIDs suitable for detecting the CMB, technologists carefully removed the membrane under the components prone to such noise. The remaining membrane also adds a layer of protection from cosmic rays that might otherwise cause non-suspended devices to malfunction.

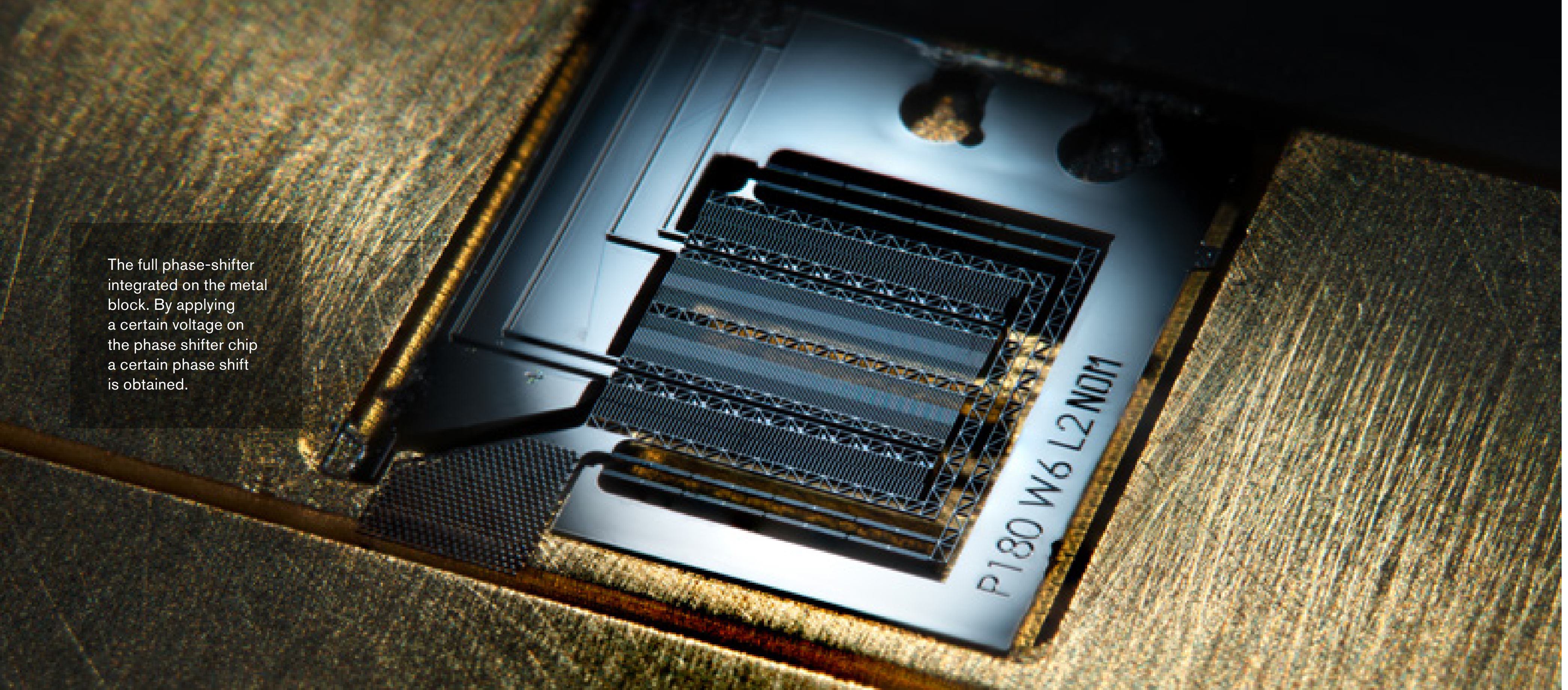
The new design can observe frequencies as low as 30GHz and as high as 30THz. This TKID is optimized for the 30-300GHz range—ideal for near-term CMB experiments. These TKIDs will be field tested in the BICEP Array Telescope at the South Pole over the 2022 Austral Winter, where noise and stability will be tested while observing CMB at 150 GHz and higher. They also demonstrated low cosmic ray strikes compared to high rates seen in older KIDs using the same materials. In these first applications, TKIDs show high optical efficiency, well-formed beams, and detect waves at the targeted spectrum frequency.

These demonstrations provide a pathway for maturing these TKIDs to wider applications. In the near term, they can be used on other terrestrial CMB telescopes to boost efficiency. TKIDs can support satellite-based CMB telescopes, such as LiteBird, PICO, and CORE. Sub-millimeter telescope observatories, which provide important data for clarifying the process of star formation and lifecycle, would also benefit from these TKIDs.

STEER HERE

21

Phased-array antennae for sub-millimeter wavelengths



The full phase-shifter integrated on the metal block. By applying a certain voltage on the phase shifter chip a certain phase shift is obtained.

MEMs based phase shifter at submillimeter wavelengths. A silicon slab is actuated in and out of a waveguide, thereby controlling the phase shift.

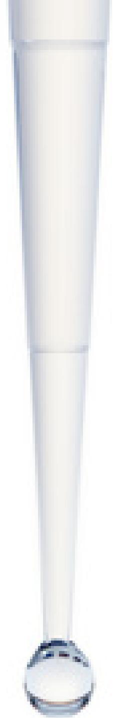
TRADITIONAL PHASED-ARRAY ANTENNAS DO NOT OPERATE WELL AT SUBMILLIMETER WAVELENGTHS; THIS BARRIER HAS BEEN OVERCOME THANKS TO MICRO-MACHINING, NOVEL MATERIALS, AND INNOVATIVE PHASED ARRAY GEOMETRIES.

Most of what can be seen in the Universe is not visible to our eyes, because the range of light we can actually see is just a small fraction of all the light there is. We use technology to see what human eyes cannot, like infrared, and microwave radiation. There is a range of light referred to by researchers as the “Terahertz gap” that is less accessible due to barriers in technology development. These wavelengths offer insights to atmospheres, structures of the Universe, as well as security and biomedical applications. Recent advances in phased arrays and electronic beam steering have revolutionized microwave science. These instruments scan the atmosphere as they orbit on satellites without the need for extra mechanical systems taking weight and space on a spacecraft while also limiting maximum scanning speeds. A phased array requires a phase shifter to electronically steer its signals. However, integrated circuit technologies most commonly used to fabricate phase shifters in the microwave regime cannot operate above 200 GHz without considerable loss. Current phased array geometries would also need to be unreasonably large to function in this range of light.

Technologists have made use of recent advances in silicon machining and micro-electromechanical systems (MEMS) to achieve a new lightweight electronic steering system. This system uses a new phase shifter to steer the main sensing beam electronically, allowing for an integrated low-power and low-volume beam scanning system for submillimeter-wave spectrometers and radars. This approach increases the number of observable targets while dramatically reducing the weight of the system.

Silicon micro-machining allows for new lenses, in turn allowing for new phased array designs. Operating in the 500-600GHz range, this technology requires fewer lenses for the array to achieve the much finer sensing needed for these spectrometers. Unlike previous limited-scan arrays, this architecture can reach large steering angles.

This advance allows small satellites to carry science instruments once reserved for flagship missions. It is directly applicable to the study of the atmospheres of Earth and other planets, but that’s only the beginning. These innovations can also be applied to instruments measuring the surface properties of cold bodies, growing our understanding of interstellar formation and dynamics. This range of signals is also useful for studying material compositions, which is very useful to exploration of outer space. Indirectly, these advances could benefit security and biomedical applications that rely on the same wavelengths for seeing inside containers or living cells.



A dropper carefully putting a liquid sample into the Chemical Laptop's sample inlet. This is the first step in the automated analysis performed by the Chemical Laptop.

Facing page: The complete Chemical Laptop is shown here, running an analysis. This system represents the first demonstration of a portable, remotely controllable instrument that can receive a liquid sample and analyze it in a completely automated fashion.

DISTANCE LEARNING

22

A portable automated lab to find life in space

Scientists use complex equipment to study and monitor the abundance of life here on Earth. As scientists direct their gaze to the skies, searching for life beyond Earth, they are faced with additional challenges. Evidence of life is extremely subtle, requiring advanced detection methods. To travel around the solar system, these instruments need to be compact as well as sophisticated. As we conduct missions further into space, analysis must also be performed with minimal human oversight.

The Chemical Laptop is a fully automated, portable, miniaturized laboratory that analyzes soil, ice, and water for signs of life. The system accepts a sample and prepares it for analysis by mixing it with a fluorescent dye using a set of microvalves integrated within a glass microchip. Using this reprogrammable microchip, scientists can perform remote analysis with better than parts-per-billion sensitivity just by sending commands through the computer. Once the sample is ready for analysis, a tiny volume is transferred to a microchannel where organics are separated by using electricity. A detector at the end of channel captures light emitted by the organics once they pass through a laser beam. Analyzing this light, the system can identify and quantify key biomolecules if they are present.

The system is the first battery-powered, remotely controlled instrument that can receive and analyze a liquid sample without user intervention. This technique has been miniaturized before, but previous instruments required manual steps and commands to prepare, load, and analyze the sample. The Chemical Laptop needs only a single command to receive, prepare, and analyze a liquid sample.

In 2019, the instrument was mounted on a rover and tested during a simulated Mars mission in Chile's Atacama Desert. To analyze solid samples, an extraction unit was coupled to the instrument for the first time. This test marks the first demonstration of fully automated analysis of soil samples, laying the foundation for future missions seeking life beyond Earth. The Chemical Laptop can be adapted to search for life on different ocean worlds such as Europa, Enceladus, or Titan.

Thanks to the reprogrammable microchip, the system can also support various analyses on Earth. Potential applications include point of care testing, precision agriculture, oceanography, and more. For example, the instrument's portability allows for environment monitoring directly in the field. On-site analysis saves the cost and time of transporting samples to a lab while offering the same or better levels of sensitivity.

REPROGRAMMABLE MICROCHIP MANIPULATES THE LIQUID FOR ANALYSIS, EXECUTING STEPS THAT SCIENTISTS NORMALLY CARRY OUT IN A LABORATORY.

This is a close up of one of the major innovations inside the Chemical Laptop: a reprogrammable glass microchip that handles liquid samples. Electrophoresis uses an electric charge to separate different particles in a liquid, in this case, amino acids and other organics to detect life.

MODEL BEHAVIOR

23

Mass produced machine learning

In our increasingly data-driven world, machine learning has become crucial. From sending emails to driving cars, machine learning takes on mundane, repetitive, and time-consuming tasks so humans can direct their energy to more challenging pursuits. However, for a machine to learn, someone has to teach it first. Human analysts must label and curate the data, develop the model, evaluate performance, and test to find the best model for a particular problem. Working under DARPA's Data Driven Discovery of Models program, data scientists have developed a tool to automate these steps.

A machine learning architecture, AutoML Applications, further automates data science. The application can select, configure, deploy and evaluate models, determining the best one for a given task. The tool assembles the models into machine learning pipelines, which are tested for accuracy, performance, and precision. The pipelines can be tested for thousands of different machine learning tasks, including image, text, video, remote sensing, and statistical data tasks, with baseline solutions for all of the problems.

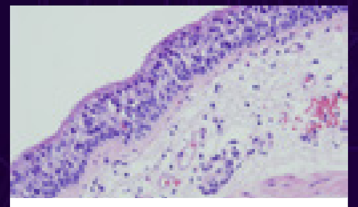
By automating these steps, this technology allows analysts to quickly try thousands of models to solve a single problem. Within hours of running hundreds to thousands of models in different pipelines, the application selects the best model for the given task. This technology performs like an army of data scientists tackling the problem when, in fact, there may be only a few subject matter experts informing the system. This technology has already fed into commercial offerings such as DataRobot, Google's AutoML project, AutoSKLearn, and AutoKeras.

AutoML can test models for power estimation on Mars rovers, and then select the best one based on terrain images. Evaluating autonomy models could also help spacecraft and robotic platforms choose the best targets for science exploration. This same tool can automatically label the vast amount of imagery science missions produce, and assist scientists with identifying the best analyses to perform.

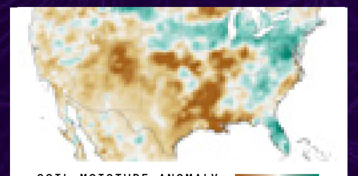
The range of applications demonstrated with AutoML, such as state of the art cancer diagnosis, crop yield prediction, weather prediciton, and instrument design, demonstrates the broad applicability of machine learning to a diverse set of problem areas.

MACHINE LEARNING ARCHITECTURE SIMULATES AN ARMY OF DATA SCIENTISTS RUNNING THOUSANDS OF MODELS TO SOLVE ALL KINDS OF PROBLEMS.

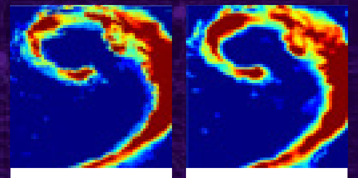
A SELECTION OF AUTOML APPLICATIONS


LUNG SPECIMEN ANALYZED BY AUTOML

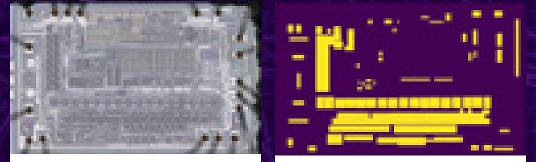
LUNG CANCER DETECTION
AutoML has demonstrated a superior ability to diagnose cancer than experts. When diagnosing thyroid cancer, it was accurate 94% of the time, compared to 85% for experts.


SOIL MOISTURE ANOMALY

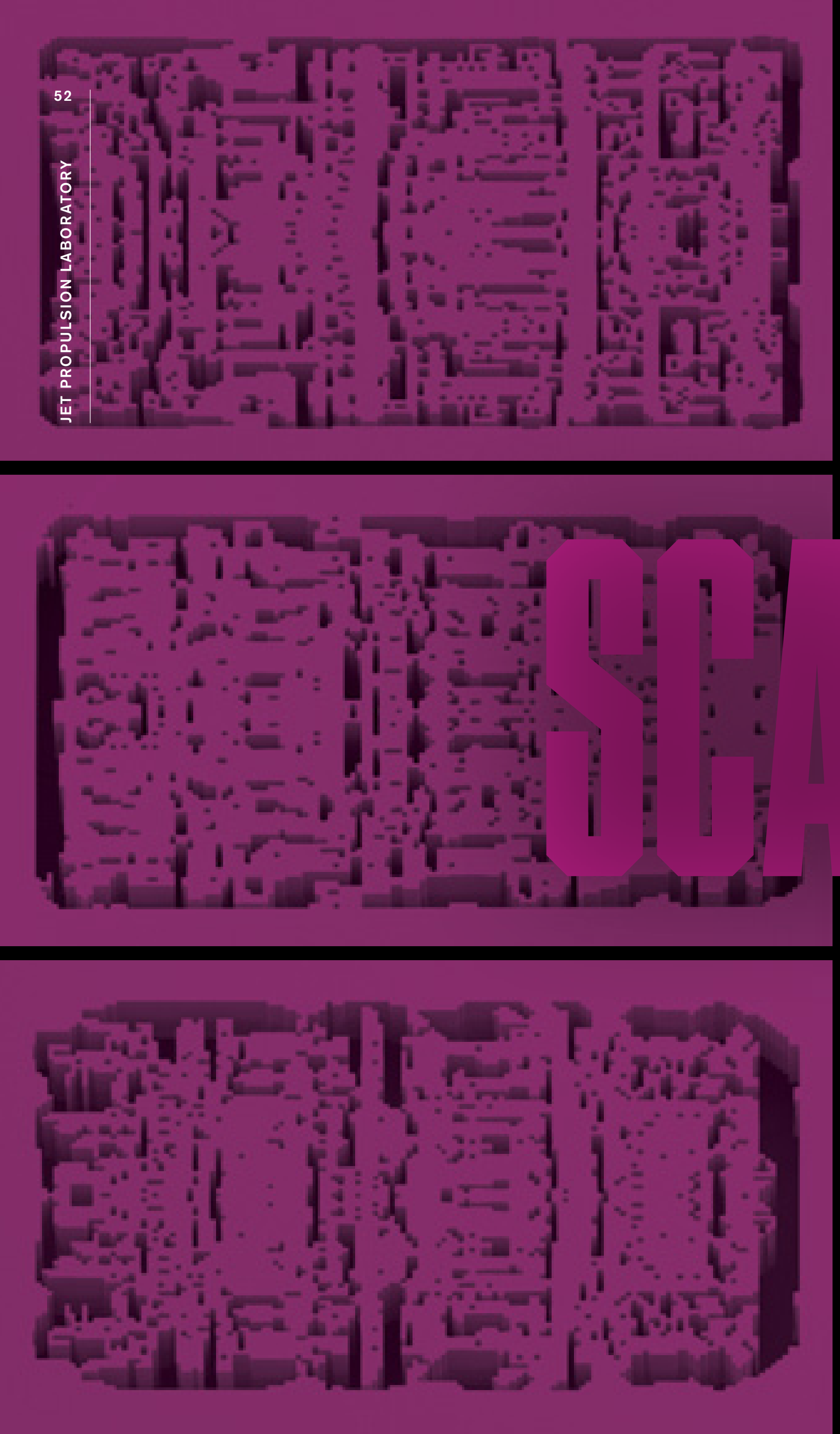
CROP YIELD
Automatic exploration of estimates for soil moisture from satellites promises to increase crop yield by an order of magnitude.


OBSERVED PREDICTED

MICROWAVE SCIENCE
This false color hurricane image represents the synthesis of precipitation data, using AutoML, from multiple spacecraft.


ELECTRONIC DYE PREDICTED MASK

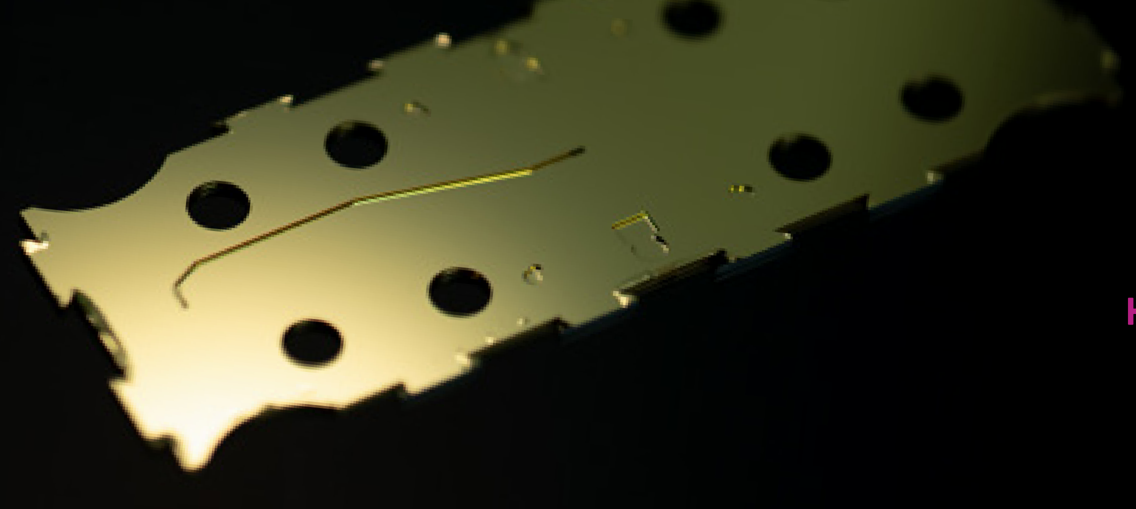
INSTRUMENT DESIGN
AutoML also has hardware applications: it is being used to map circuits and sub components to design electronics more efficiently.



SCALING UP

24 Breakthrough in computational design of metamaterials

Metamaterial etched on silicon for polarization control of the electromagnetic wave. These designs are meant to be stacked to create a 3D structure.



A silicon component that comprises part of the sensor. A stack of these pieces, containing the detector and 3D metasurface, comprise the receiver.

3D METAMATERIALS REVOLUTIONIZE THE DESIGN OF HIGHLY PRECISE AND COMPACT SENSOR SYSTEMS

Venus is a formidable planet, with an atmosphere 90 times denser than Earth's and surface temperature hot enough to melt lead. Yet, scientists believe Venus was once like Earth, formed from similar materials and mostly ocean. Venus's atmosphere, with its many different layers of gas and chemicals, may offer some insight into why this nearby planet evolved so differently from Earth. Scientists can view these gases and chemicals in the submillimeter range, using dualband systems. These systems use large reflectors and two separate receivers to detect phenomena in this range.

Metamaterials present a way to reduce the size, weight, and complexity of multiband systems for the submillimeter range. Metamaterials are artificial, and can be precisely tailored to manipulate electromagnetic waves, improving the efficiency and bandwidth of diffractive optical elements, such as lenses.

These materials could be used to focus the electromagnetic radiation of multiple spectral bands on a single, integrated receiver. However, most metamaterials are made with only one layer of diffractive elements. As a result, they have highly limited bandwidth, restricting their applications for broadband or multi-band observations.

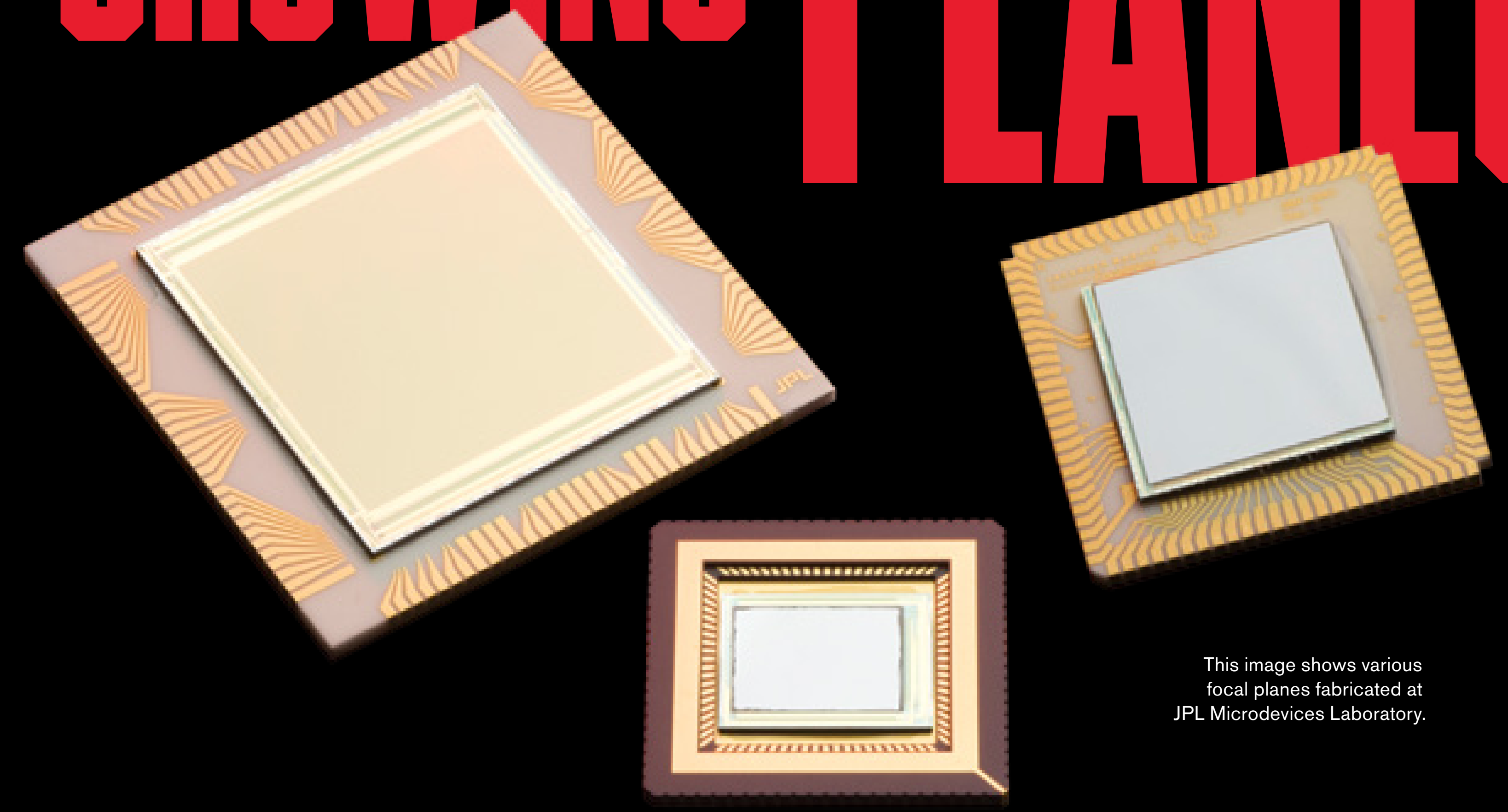
Technologists have used new computational methods to develop a new class of 3D metamaterials to improve bandwidth and enable multi-spectral observations in the submillimeter range. The 3D metasurface is stacked with multiple patterned silicon wafers, which are assembled together within the same wafer-stack. This extra dimension offers control across broader bandwidths and high numerical apertures. Using this next generation metasurface technology, a high gain primary antenna can directly focus the radiation on two integrated side-by-side waveguide-based receivers.

The result is a highly compact multi-spectral instrument, enabling broadband and multi-frequency submillimeter-wave spectroscopic observations on the same radio wave receiver. The new approach offers greater efficiency and sensitivity, all while being able to detect many types of light and radiation. This could give a satellite small enough to hold in your arms the same power for science return as a flagship mission.

Scientists can use this technology to conduct limb-sounding measurements of planetary and cometary atmospheres. These measurements tell us about the distribution of gases and temperature profiles in the stratosphere and mesosphere—all important data about atmospheric formation and evolution. This versatile platform also offers more freedom in its signal design and control, benefitting numerous other applications in NASA and the research community at other wavelengths ranging from microwaves to the infrared.

25 Warming up to new missions

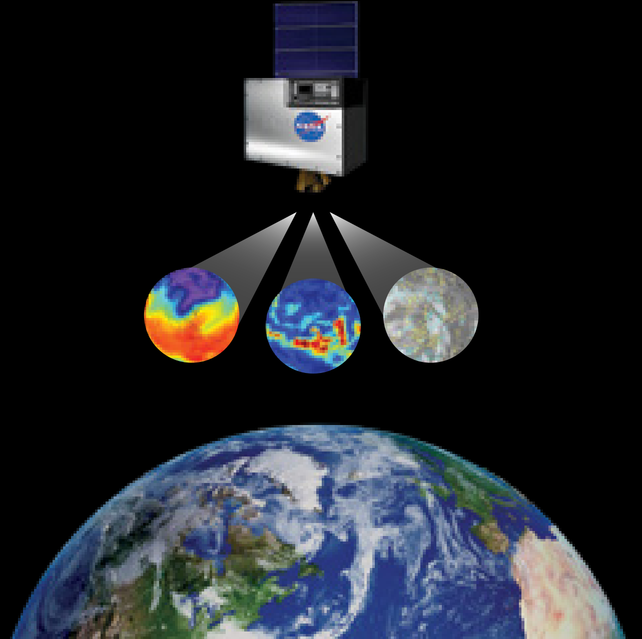
GROWING PLANES



This image shows various focal planes fabricated at JPL Microdevices Laboratory.

ADVANCED MATERIALS AND MANUFACTURING TECHNIQUES ENABLE THE HIGH OPERATING TEMPERATURE BARRIER INFRARED DETECTOR (HOT-BIRD), PUTTING MORE INFRARED SCIENCE IN THE REACH OF SMALLSATS THAN EVER BEFORE.

Artist rendering of an infrared remote sensing SmallSat in low Earth orbit.



On the electromagnetic spectrum, infrared light is the closest thing to visible light that the human eye cannot see. Infrared (IR) detectors allow us to see in this wavelength, helping us to unveil hidden objects. For example, astronomers use IR detectors to uncover newly formed stars, study early galaxy formation, and detect cold nebulae. Scientists have been striving to improve on IR detector designs for decades. Current detectors are expensive to manufacture and fragile. Most designs are also limited to operation at extremely low temperatures, requiring costly, cumbersome cryocoolers.

The High Operating Temperature Barrier InfraRed Detector (HOT-BIRD) uses a novel material to operate at high temperatures while covering a wide range of the IR spectrum—mid, short, and near. Using carefully chosen elements and alloys, atoms are deposited onto a special substrate material and coaxed into orderly rows. The atoms are grown into 3D crystalline structures called superlattices. These lattices are assembled into the focal arrays used to capture infrared images. The final product is only 5 to 10 microns thick, which is about the width of spider web silk. Almost every aspect of the process can be customized to achieve specific results.

The material combines the advantages of the most commonly used materials for IR detectors, Mercury Cadmium Telluride (MCT) and Indium antimonide (InSb). MCT has tremendous flexibility over a wide range of the IR spectrum and can operate at higher temperatures.

However, MCT is also soft and brittle, requiring expensive care for growth, fabrication, and storage. On the other hand, InSb is sturdier but requires much lower temperatures to function. HOT-BIRD's material construction offers the best of both worlds: it combines the higher operating temperatures and versatility of MCT with the strength of InSb.

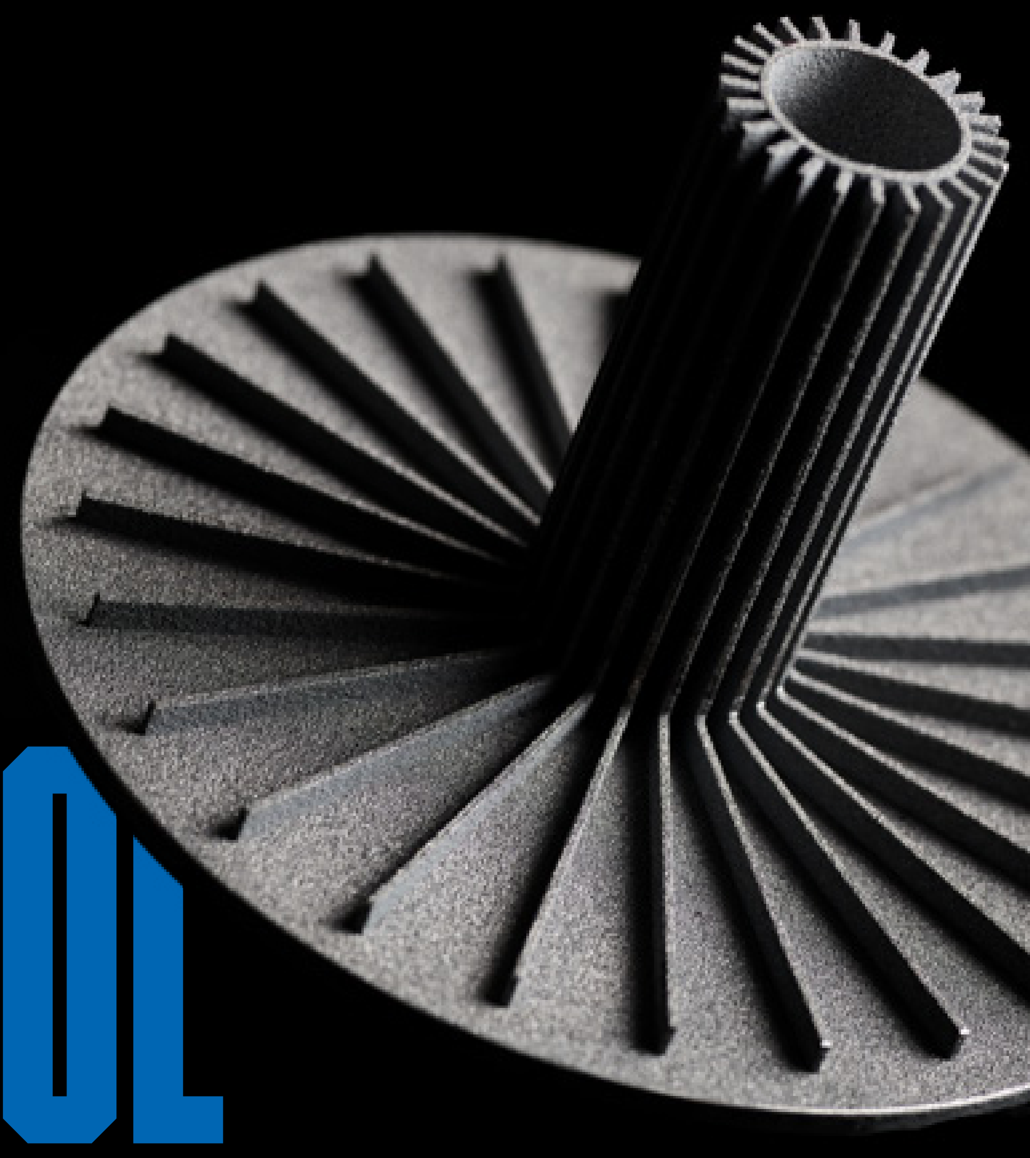
The higher operating temperatures of this material, combined with its lower manufacturing costs and customizability, open infrared detection up to a wider range of applications. BIRD focal planes drastically lower the cooling demand on an active cooling system in low Earth orbit, significantly reducing size, power, cost, and complexity. With these improvements, SmallSat missions could add infrared detection their assortment of capabilities. Low-cost SmallSat constellations can help us image landforms on Earth or other planetary bodies, reveal ice for resource mining on the Moon, and enhance weather detection and prediction. On Earth, emergency responders can use the data from SmallSats equipped with HOT-BIRD focal planes to search for and fight fires, allowing them to see through haze and smoke.

An image taken with a HDTV format long-wavelength barrier infrared detector (BIRD) focal plane.

No more exploding batteries

PLAY IT COOL

26



A closeup of a battery case, showing a design that can only be achieved thanks to advanced manufacturing and 3D printing techniques.

We are sending smaller space systems on longer missions to distant, harsh locations, presenting new challenges to assured energy access. Space exploration systems typically generate energy with solar panels or nuclear reactors. However, panels are not always in view of the sun, or are obscured in dust storms on Mars. Reliable energy storage can be the difference between a mission ending early or being extended.

In the last two decades, the world has turned to Lithium (Li)-ion batteries, for both Earth and space-based applications. They can hold very large amounts of energy in small volumes, and accommodate high power outputs. They also degrade much slower than previous battery technology, making them ideal for long-term missions. However, these advantages come with risks. The chemistry of Li-ion cells is volatile and sensitive to operating temperature. If they get too hot, the cells become less effective at storing and outputting energy. In the worst-case scenario, poor thermal control can lead to explosions known as "thermal runaway". This can be truly catastrophic, as high performing Li-ion batteries can have power densities as high as 1/5 that of TNT.

Additively manufactured battery cases with embedded heat pipes can control the operating temperature of Li-ion batteries in a mass efficient package. These cases use 3D-printing techniques to embed high-performance, conformal heat pipes directly into the battery case structure.

By utilizing the exceptional two-phase heat transfer capability inherent to heat pipes, this design enables the efficient transfer of heat generated within the cells to the external environment. The result of this innovation is a monolithic battery case with integrated two-phase thermal control that can enable high power operation of Li-ion cells while also inhibiting the propagation of thermal runaway. By embedding the heat pipes directly into the case, the effective thermal conductivity of the structure can be increased to enables much greater control over the batteries' temperature, enables high power operation and can prevent a catastrophic explosion.

3D-PRINTED CASES USE HEAT PIPES FOR BUILT-IN THERMAL CONTROL, ENSURING LI-ION BATTERIES STAY COOL AND SAFE AS THEY POWER DISTANT MISSIONS.

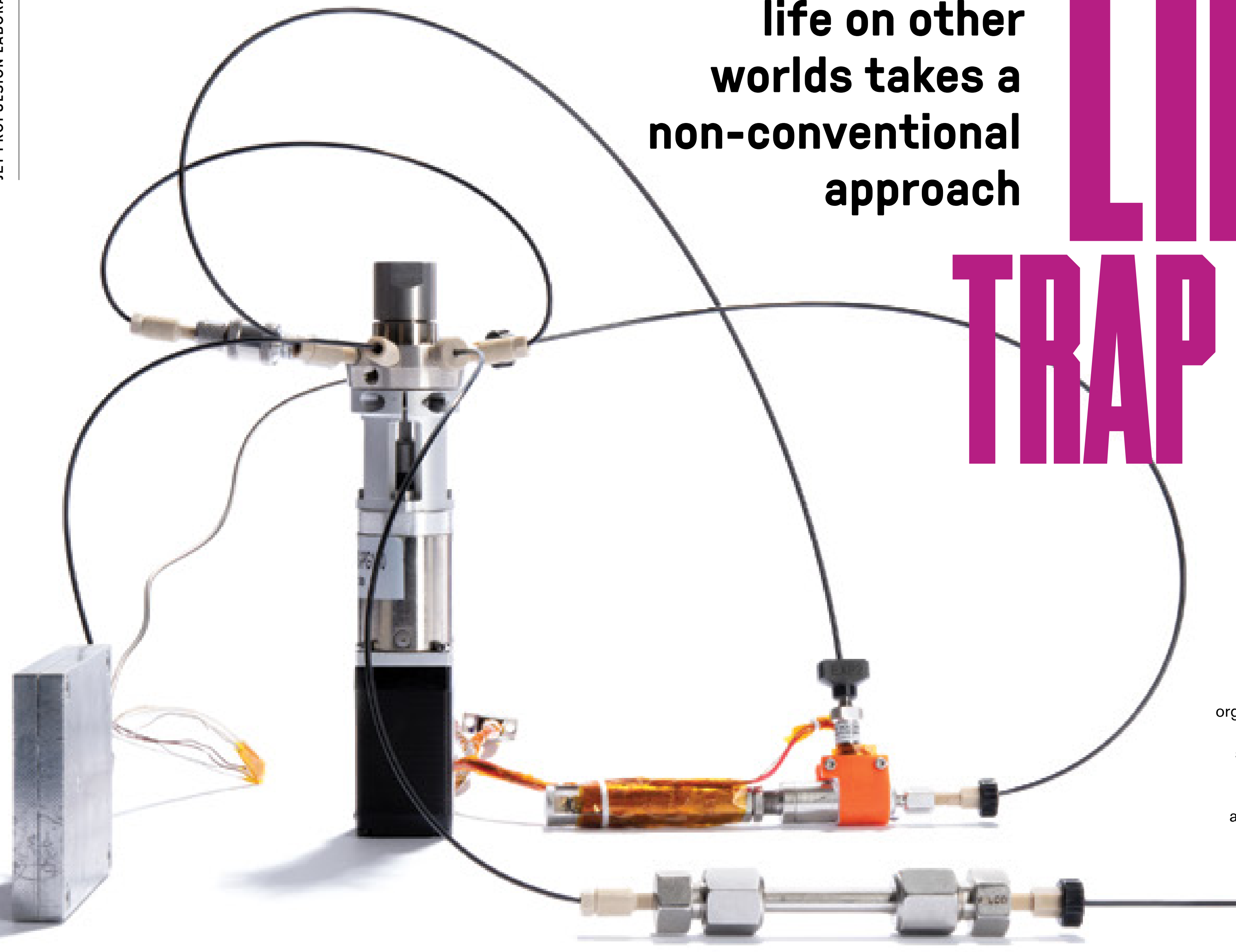
Effective temperature control is not only needed by space systems; the innovations made here apply to power generators. Because this battery case is 3D printed, it can be adapted to nearly any form, and implemented faster, and for less cost, than traditional thermal management systems. This kind of innovation will also be critical to electric vehicles, where weight, high power operation, and safety are all critical.

4 versions of battery casings specifically designed to prevent thermal runaway in Lithium-Ion batteries. The use of oscillating heat pipes built into the structure is the major innovation in this design.

LIFE TRAP

Finding organic life on other worlds takes a non-conventional approach

27



The sub-system extracts organics from a solid or liquid sample and sends it for sensitive chemical analysis at parts-per-billion levels. Transport of organics is achieved by manipulation of temperature and pressure.

Life leaves “fingerprints” everywhere it goes, often through distinct chemical compounds. These clues tell us about where life has been, what it is like now, and where it can potentially thrive. Scientists are now searching for these fingerprints elsewhere in the solar system, seeking to find signs of life on other planets and moons. Astrobiologists take samples from other planets and perform chemical analyses to search for biomarkers—traces of compounds left by organisms. Scientists need to remotely conduct these sensitive analyses on site, avoid any sample contamination, work in low gravity, contend with unknown sample types, and be able to analyze samples for a wide range of biomarkers, since we don’t know what life might look like on other planets. Current technology is not optimized to accept the wide range of samples that could be present on or under the surfaces of exotic planets or moons, not to mention contamination issues. Past missions were able to discover thiophenes and other small aromatic hydrocarbons on Mars using heat and organic reagents. However, the organic reagents contaminated the samples, making it difficult to reliably identify native species.

A versatile new instrument reduces contamination risk by using supercritical CO_2 to extract and separate molecular species from a sample, whether it is solid, liquid, acidic, high-pH or anything in between. Supercritical CO_2 is carbon dioxide above its critical temperature and pressure, acting like a gas with the density of a liquid. The instrument operates at low to moderate temperatures (35-150 °C), allowing for the analysis of heat-sensitive molecules. The technique uses only simple, non-organic solvents, so the samples are safe from being contaminated, fragmented, or oxidized. These solvents flow through a sample, extracting organic molecules, while collecting them in a solid-phase trap column. The trap column is loaded with a material that will attract—or “trap”—the target organics while the rest of the solvent flows through the system. The trap column concentrates the molecules down for analysis, allowing their identity and concentration to be determined at the sub-parts-per-billion level.

For the first time online supercritical fluid extraction and separation has been demonstrated without any organic modifier. This technique is safer for the sample, and reduces total analysis time, since supercritical CO_2 has lower surface tension than conventional liquids. The system can complete its analysis in just 30 minutes. Specifically designed for on-site life detection on planetary bodies, this technology helps us more efficiently and reliably search for unknown, diverse signs of life and habitable environments on exotic worlds such as Europa, Enceladus, Titan, and beyond.

“It’s a trap!” The smallest component pictured here, called a trap, concentrates a sample’s organics down to a volume of 2.4 microliters (reducing its volume by a factor of ~1000).

LIFE-DETECTION INSTRUMENT USES SUPERCRITICAL CO_2 INSTEAD OF ORGANIC CHEMICALS, ALLOWING FUTURE MISSIONS TO TEST MORE ACCURATELY, QUICKLY, SIMPLY, AND SAFELY

GROWING WITH THE GRAIN

28

3D printing magnetic properties into materials

The magnetic shielding components for a high performance Magnetically Shielded Miniaturized (MaSMi) Hall thruster can be fabricated in better than half the time using additive manufacturing.

Hall thrusters offer slow, steady electric propulsion for stationkeeping, orbit raising, extending the life of satellites, and propelling spacecraft in deep space. In the past decade, engineers have begun magnetically shielding these thrusters, to reduce erosion and extend the life of the thruster. Soft magnetic alloys are typically used to achieve magnetic shielding. These alloys have high magnetic saturation and permeability with low coercivity and low core loss. Unfortunately, while such alloys demonstrate excellent magnetic properties, they also tend to be brittle, making it difficult to machine these materials. In addition, standard manufacturing and processing methods tend to degrade the magnetic properties of these alloys, diminishing their performance.

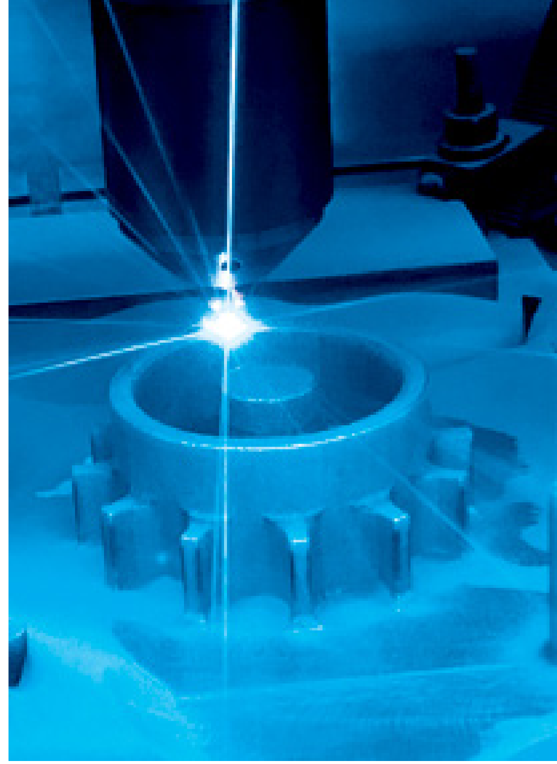
Technologists are utilizing a new manufacturing technique, called Directed Energy Deposition (DED), that optimizes the magnetic and structural performance of soft magnetic alloys. The alloy is first powderized for use as feedstock. During deposition, the alloy goes through a series of heating, cooling, and re-heating to shape and tune the material. This cycle of cooling and heating creates an internal energy that is stored in the printed object. This internal energy can be used to recrystallize and grow grains during later heat treatment.

Grain size dictates magnetic and mechanical properties: coarse grains result in better soft magnetism while fine grains result in more mechanical strength.

By controlling grain size, engineers can print a fine grain material that is easy to machine and heat treat it to a coarse grain microstructure to architect powerful magnetic properties. Also, considering the magnetic texture in the design of the magnetic circuit would improve the performance of magnetically shielded hall thrusters. The 3D printing technique also allows unique processing considerations, such as radial deposition, that could enable radial texturing of the magnetic properties—a process not achievable using traditional manufacturing processes.

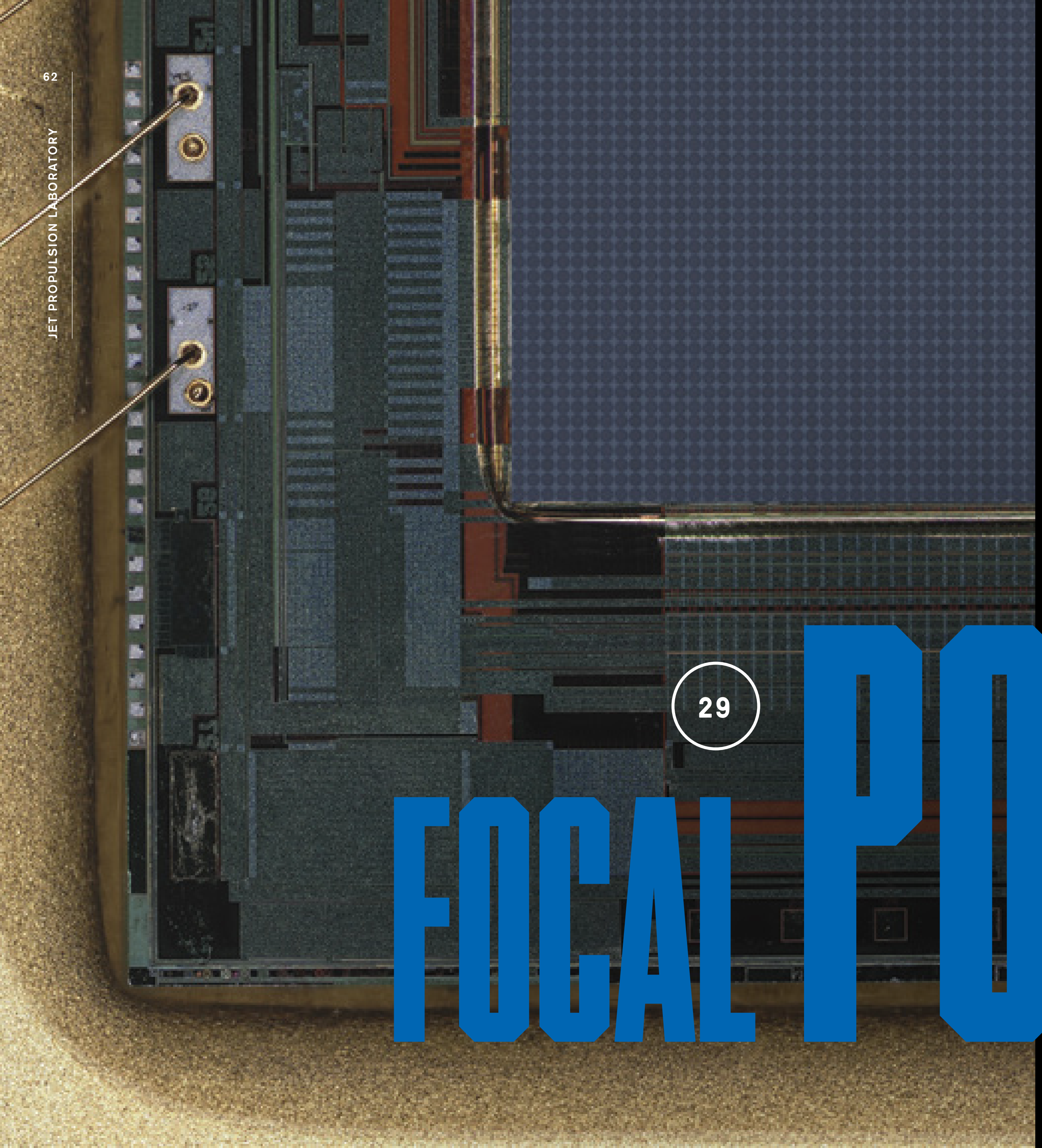
This technology can be used to print any element where soft magnetic alloys are useful, such as high-performance motors, high-efficiency generators, solenoids, and sensors. This process reduces cost and accelerates manufacturing times, while also optimizing the element's performance for its given application. The manufacturing approach also allows for larger elements, such as Hall thrusters, to be fabricated as a monolithic structure. Eliminating the need for bolted joints improves system performance and reliability, simplifying the structure and distributing the magnetic properties throughout the structure.

DIRECTED ENERGY DEPOSITION ALLOWS PRINTING MATERIALS WITH GRADIENTS OF DIFFERENT MAGNETIC PROPERTIES IN A SINGLE STRUCTURE: IN THIS CASE, FOR HALL THRUSTERS.



Above: Directed Energy Deposition (DED) of a soft magnetic alloy for a Magnetically Shielded Miniaturized (MaSMi) Hall thruster component.

Below: The grain structure of the soft magnetic alloy controls both the magnetic and mechanical properties. The Electron Back Scatter Diffraction (EBSD) image shown here provides information on the grain structure.



Left: A closeup of the metalens array that has been bonded to microchip circuitry. The array is in the upper right corner, full of small blue circles, outlined in gold.

Right: A closeup of one of those circles shows how the technology is designed at the microscopic level. Each one of these metalens is only 30 microns wide: that's less than half a human hair.

Micro sensors designed from the atom up

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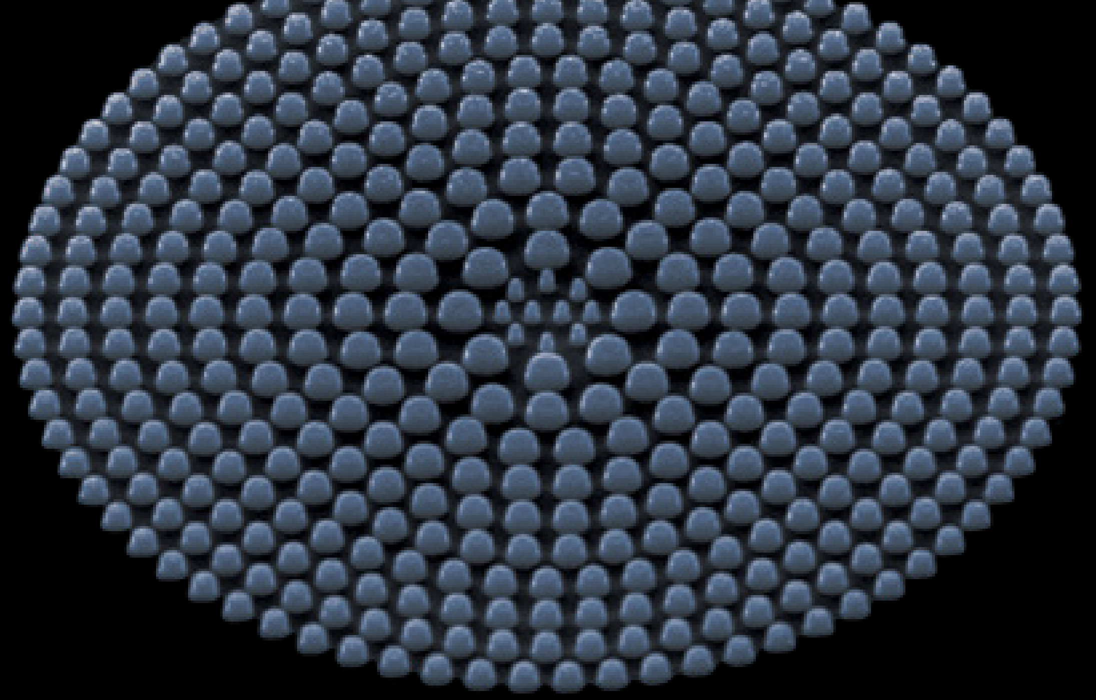
FOCAL POINT



METALENS ETCHED DIRECTLY ON TO THE DETECTOR SURFACE CONCENTRATES THE LIGHT THE SENSOR RECEIVES: ENABLING THE SYSTEM TO CAPTURE MORE DETAIL EVEN WHILE OPERATING AT HIGHER TEMPERATURES.

Since the discovery of infrared (IR) light in 1800, astronomers have used IR detectors to see with light invisible to human eyes. Animals, like snakes, have been seeing IR light for much longer than us, though only for survival. Modern IR imagers are often made with focal plane arrays (FPAs), in which many tiny IR sensors are organized in a large matrix to construct an image. These devices are the most advanced imaging tools for an infrared imaging, as well as spectroscopy, night vision and manufacturing inspection, to name just a few applications.

To reduce unwanted internal noise, these infrared FPAs operate at low temperatures, requiring expensive, large, and heavy cryocoolers. One way to work at higher temperatures is to reduce the active volume of the detector. However, this means less light for the detector. To address this challenge, solid-immersion metalens for use in IR FPAs has been developed in collaboration with Harvard University.

A metalens concentrates the light entering the sensor, enabling the detector to get the most light despite reduced size. Unlike standard curved lenses, like those on your eyeglasses, each metalens is a flat structure, with specially designed tiny pillars that redirect the light toward the sensor. To be integrated with FPAs, a metalens must be made of the same materials as the detectors in the FPA and be fabricated using a compatible manufacturing process.

To meet these requirements, this solid-immersion metalens is etched directly onto the surface of the substrate on which FPA detectors are grown. Located on the back of the detector, the lens focuses light straight into the detectors. The flat lens is efficient, improving light collection by 300%. Due to the circular shape of the pillars comprising the flat lens, it works for all light polarizations necessary. Finally, at 30 micrometers, this metalens is a first flat optical concentrator operating in IR having the potential to be integrated with each pixel of the FPAs.

These breakthroughs pave the way for the direct integration of future metalenses into FPAs, opening infrared detection up to a wider range of applications. The solid-immersion metalens reduces the need for an active cooling system on new infrared sensors, substantially reducing size, cost, and complexity. It will also make conventional uses more efficient: astronomy, medicine, weather sciences, even art conservation could benefit from improved IR detector systems.

CONTRIBUTOR PROFILES

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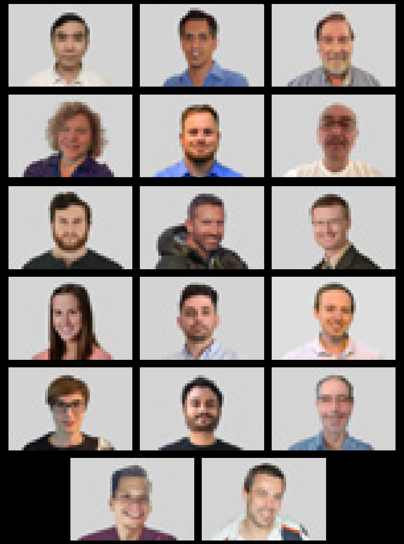
Team: Vinh Bach, Mahmood Bagheri, Rob J Calvet, Barbara Cohen, Matthew J Fling, Siamak Forouhar, Luke Hardy, Paul Hayne, Matthew Kowalkowski, Jessica Loveland, Lini Mestar, Robert Miller, Mina Rais-Zadeh, Aadil Rizvi, Glenn R Sellar, Jacob Shelton, Quentin Vinckier



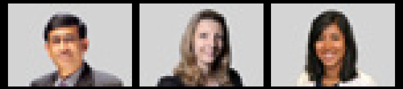
MARIA ALONSO | P. 46 & P. 52

Principal Investigator, Terahertz Phase Shifter & 3D Metamaterials

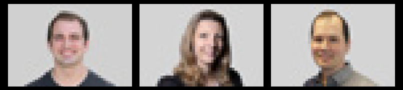
Dr. Alonso-delPino received her PhD in Electrical Engineering from the Technical University of Catalonia. At JPL, she was a researcher with the Submillimeter-Wave Advanced Technology group in the development of innovative antennae and RF systems. Today, she is an Assistant Professor at the Technical University of Delft.

Terahertz Phase Shifter Team: Goutam Chattopadhyay, Cecile Jung-Kubiak, Sofia Rahiminejad

3D Metamaterials Team: Conner Ballew, Cecile Jung-Kubiak, Andrei Faraon



Terahertz Phase Shifter



3D Metamaterials

LAURIE BARGE | P. 34

Principal Investigator, Planetary Test Beds

Dr. Barge received her PhD in Geological Sciences from the University of Southern California. She is a Scientist in the Laboratory Studies Group at JPL. Her research interests include chemical and geological processes on other planets, and works on hydrology, phosphorous redox, and atmospheric science.

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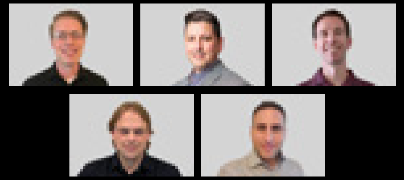

RALPH BASILIO | P. 6

Project Manager, OCO-3

Dr. Basilio received his PhD in Aerospace Engineering from the University of Southern California. He is the Program Manager for Earth Science Competed Missions at JPL, and the Project Manager for OCO-3. His work includes Earth science and near-Earth object space missions.

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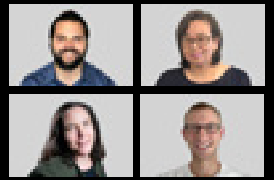

CHARLES BEICHMAN | P. 32

Principal Investigator, Frequency Combs

Dr. Beichman received his PhD in Astronomy from the University of Hawaii. He is a Senior Research Scientist, a JPL Fellow, and Executive Director of the NASA Exoplanet Science Institute at JPL and Caltech. His research interests include the search for exoplanets, infrared astronomy, and precision modeling.

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Principal Investigator, Frequency Combs

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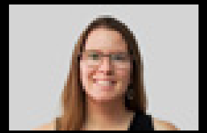

KALIND CARPENTER | P. 26

Principal Investigator, DASHER

Mr. Carpenter received with MS in Mechanical Engineering from the California State University, Los Angeles. He is a Robotics Mechanical Engineer in the Robotic Vehicles & Manipulators Group at JPL. His research interests include multi-agent robotic teams, in situ sampling, and mobility.

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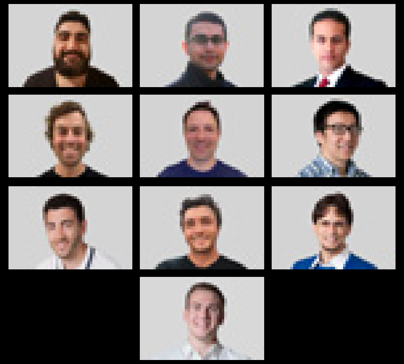

RYAN CONVERSANO | P. 16

Principal Investigator, ASTREUS

Dr. Conversano received his PhD in Aerospace Engineering from the University of California, Los Angeles. He is a Technologist in the Electric Propulsion Group at JPL. His research interests include electric propulsion, small spacecraft systems, and additive manufacturing.

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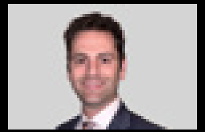

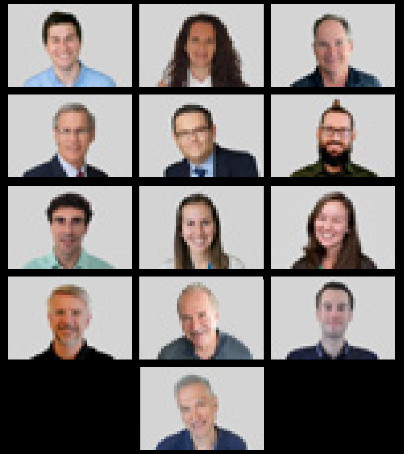

CONTRIBUTOR PROFILES

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Principal Investigators, 3D Printing Hall Thrusters

Dr. Dillon received a PhD in Materials Science and Engineering from the University of California in Irvine. He is a Technologist, and leads the Materials Development and Manufacturing Technology Group at JPL. His research interests include additive manufacturing of metal alloys and gradients, as well as materials and processes for extreme environment capable spacecraft electronics and mechanisms.

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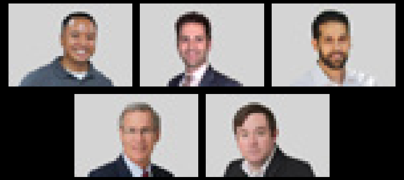
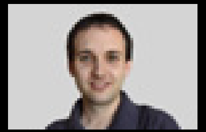


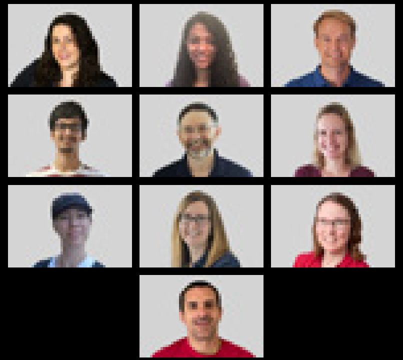
GARY DORAN | P. 24

Principal Investigator, Autonomous Science

Dr. Doran holds a PhD in Computer Information Science from Cape Western Reserve University. He is a Data Scientist in the Machine Learning and Instrument Autonomy Group at JPL. His work focuses on using machine learning and artificial intelligence to detect events and features of scientific interest onboard spacecraft.

Team: Marissa E. Cameron, Srija Chakraborty, Corey J. Cochrane, Ameya Daigavane, Ashley Davies, Ingrid Daubar, Serina Diniega, Caitriona Jackman, Kiri L. Wagstaff, Sylvain Piqueux





BEN FURST | P. 56

Principal Investigator, Li-ion Battery Case

Mr. Furst received his MS in Mechanical Engineering from the University of California in Los Angeles. He is a Technologist in the Thermal Fluid Systems and Mission Operations Group at JPL. His research interests include energy storage systems, active thermal control systems, and fluid systems.

Team: Kumar Bugga, Kurt Gonter, Stefano Morellina, Scott Roberts, Kyle Williams

CHRISTINE GEBARA | P. 20

Principal Investigator, Tensegrity Structures

Ms. Gebara received her BS in Aerospace Engineering from the Georgia Institute of Technology. She is a Mechanical Engineer in the Advanced Deployable Structures Group at JPL. Her research interests include deployable structures, tensegrity systems, and additive manufacturing.

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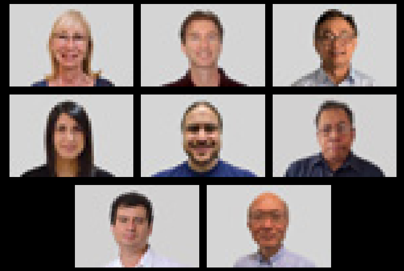
SARATH GUNAPALA | P. 54

Principal Investigator, HOT BIRD

Dr. Sarath Gunapala holds a PhD in Physics from the University of Pittsburgh. He is a Senior Research Scientist, a JPL Fellow, and leads the Infrared Photonics Group at JPL. He works primarily with infrared semiconductor devices based on quantum wells, wires, dots, and superlattice devices. He has a special interest in studying novel artificial band-gap materials for infrared detectors and imaging focal planes.

Team: Anita Fisher, Cory Hill, Sam Keo, Arezou Khoshahlagh, Brian Pepper, Sir Rafol, Alexander Soibel, David Ting



ARAM HAMIDI | P. 42

Principal Investigator, Cockatoo

Ms. Hamidi received her MS in Electrical Engineering from Santa Clara University. She is a Data Scientist in the Mission Control Systems Deep Learning Technologies Group at JPL. Her work covers machine learning, deep learning, AI assisted cybersecurity, vand data science.

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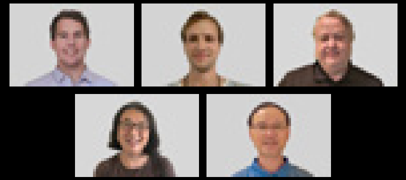
BRYANA HENDERSON | P. 58

Principal Investigator, Life Detection Instrument

Dr. Henderson received her PhD in Chemistry from the University of California in Los Angeles. As a Scientist in the Laboratory Studies Group at JPL, she investigates processes on exotic planetary environments by reproducing them in the laboratory. Her research interests include radiation chemistry and physics, evolution of organics, and detection of life in our Solar System.

Team: Victor Abrahamsson, Johannes Gross, Isik Kanik, Ying Lin, Fang Zhong

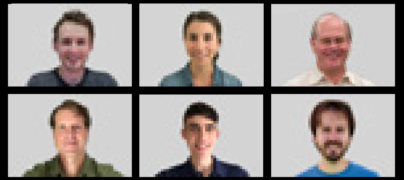


JACOB ISRAELEVITZ | P. 12

Principal Investigator, SQUID

Dr. Izraelevitz received his PhD in Mechanical Engineering from the Massachusetts Institute of Technology. He is a Robotics Technologist in the Extreme Environment Robotics Group at JPL. His research interests bridge the interface between fluid dynamics and robotics, including the design of planetary balloons, rotorcraft, and underwater vehicles.

Team: Matt Anderson, Amanda Bouman, Joel Burdick, Brett Kennedy, Paul Nadan, Daniel Pastor



CONTRIBUTOR PROFILES

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Principal Investigator, ADAM

Mr. Kahovec received his MS in Applied Mathematics from the California State Polytechnic University in Pomona. He is a Data Scientist in the Mission Control Systems Deep Learning Technologies Group at JPL. His research interests include mathematical modeling, machine learning, and optimization.

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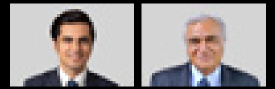

AARON KIELY | P. 22

Principal Investigator, FLEX

Dr. Aaron Kiely holds a PhD in Electrical Engineering: systems from the University of Michigan in Ann Arbor. He is a Telecommunications Engineer in the Information Processing Group at JPL. He works primarily on space telecommunications technologies, particularly specializing in spacecraft onboard data compression techniques.

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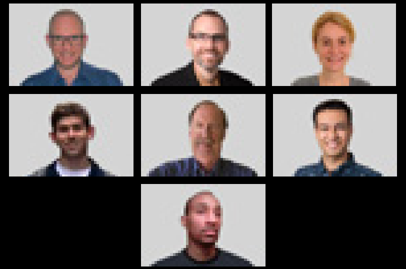
JACK LIGHTHOLDER | P. 28

Principal Investigator, Barefoot Rover

Mr. Lightholder received his BS in Computer Science from Arizona State University. He is a Data Scientist in the Machine Learning and Instrument Autonomy Group at JPL. His work includes topics on machine learning, mission operations, SmallSat systems, and planetary science.

Team: Matt Cross, Lukas Mandrake, Yuliya Marchetti, Thomas Schibler, Paul Springer, Peyman Tavallali, Devon Yates



CHRIS MATTMAN | P. 50

Principal Investigator, AutoML

Dr. Mattman received his PhD in Computer Science from the University of Southern California. He is the Manager for the Artificial Intelligence, Analytics, and Innovative Development Division at JPL. His research areas include software architecture, machine learning, and data analytics.

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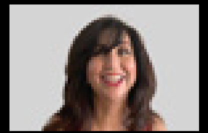
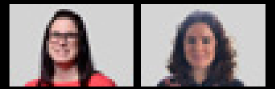
Dr. Nikzad holds a PhD in Applied Physics from the California Institute of Technology. She is a JPL Fellow, Senior Research Scientist, and the lead for the Advanced Detectors, Systems, and Nanoscience Group. Her research focus is in developing UV/visible/NIR instrument technologies and instruments specifically in high-performance silicon and gallium nitride detectors using nanoengineering, UV imaging spectrometers, and cameras.

Team: April Jewell, Gillian Kyne



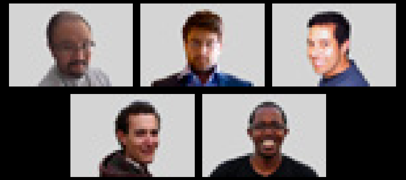


ROGER O'BRIENT | P. 44

Principal Investigator, TKIDS

Dr. O'Brient received his PhD in Physics from the University of California in Berkeley. He is a Microdevices Engineer in the Superconducting Materials and Devices Group at JPL. He works on spectral sensors for various platforms, as well as astronomical science.

Team: Clifford Frez, Lorenzo Minutolo, Bryan Steinabach, Anthony Turner, Albert Wandui



ALEXANDER SOIBEL | P. 62

Principal Investigator, Metalens

Dr. Soibel received his PhD in Physics from the Weizmann Institute of Science. He is a Microdevices Engineer in the Infrared Photonics Group at JPL. He works on development of infrared detectors and lasers.

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DAVID THOMPSON | P. 40

Principal Investigator, Radiative Transfer

David R. Thompson received his PhD in Robotics from Carnegie Mellon University. He is a Principal Research Technologist in the Imaging Spectroscopy Group at JPL. His research advances the algorithms and practice of imaging spectroscopy for characterizing Earth and other planetary bodies.

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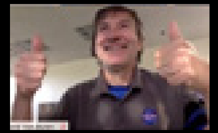
CONTRIBUTOR PROFILES

DAVID VAN BUREN | P. 36

Principal Investigator, VITAL Ventilator

Dr. Van Buren received his PhD in Astronomy from the University of California in Berkeley. He is a Systems Engineer in the Mechanical Systems Engineering, Fabrication and Test Division at JPL. His research interests include fluid systems, telescope optics, science modeling and simulation, and instrument systems engineering.



MICHAEL R. JOHNSON | P. 36

Principal Technologist on VITAL

Mr. Johnson received his B.S. in Mechanical Engineering from California State Polytechnic University Pomona. He is Chief Mechatronics Engineer in the Senior Mechanical Staff Group of Section 355. His work covers mechanical and electronic/electromechanical systems in nearly every area of JPL activity. His research interests include extreme temperature actuators and their drive electronics along with electric and hydraulic control systems.

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PETER WILLIS | P. 48

Principal Investigator, Chemical Laptop

Dr. Willis received a PhD in Chemistry from Cornell University. He leads the Chemical Analysis and Life Detection Group at JPL. He is developing liquid-based chemical analyzers that can be used in the search for life on robotic missions to ocean worlds such as Europa and Enceladus.

FERNANDA MORA | P. 48

First Author, Chemical Laptop

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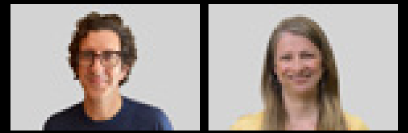
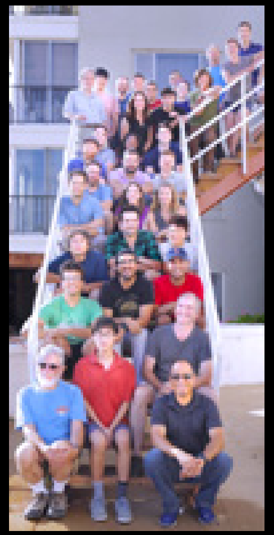


PETER WILLIS | P. 30

Principal Investigator, OWLS

Dr. Willis received a PhD in Chemistry from Cornell University. He leads the Chemical Analysis and Life Detection Group at JPL. He is developing liquid-based chemical analyzers that can be used in the search for life on robotic missions to ocean worlds such as Europa and Enceladus.



JPL Team: Chris Lindensmith, Yong Chong, Marc Foote, Aaron Noell, Carissa Weber, Andrew Berg, Konstantin Zamuruyev, Florian Kehl, Mauro Ferreira Santos, Mircea Badescu, Sarah Waller, Elizabeth Jaramillo, Nate Oborny, Jessica Creamer, Fernanda Mora, Miranda Kok, Vlad Cretu, Andrew Demartino, Timothy Leonard, Kevin Tomkins, Steve Monacos, Stewart Sherrit, Sabrina Feldman, Claudimir do Lago, Gene Serabyn, Kent Wallace, Scott Perl, Lukas Mandrake, Emily Dunkel, Shawn Anderson, Brian Bue, Gary Doran, Steven Lu, Kurt Liewer, Eric Zhong, Coleman Richdale, Brandon Metz, Jurij Simcic, Emily Kurfman, Faith Oftadeh

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USC Team: Scott Fraser, Thai Truong, Kevin Keomanee-Dizon

GAIL WOODWARD | P. 38

Principal Investigator, AUV

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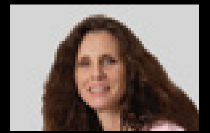
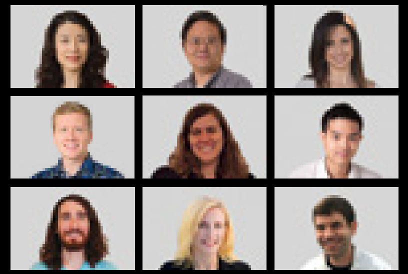
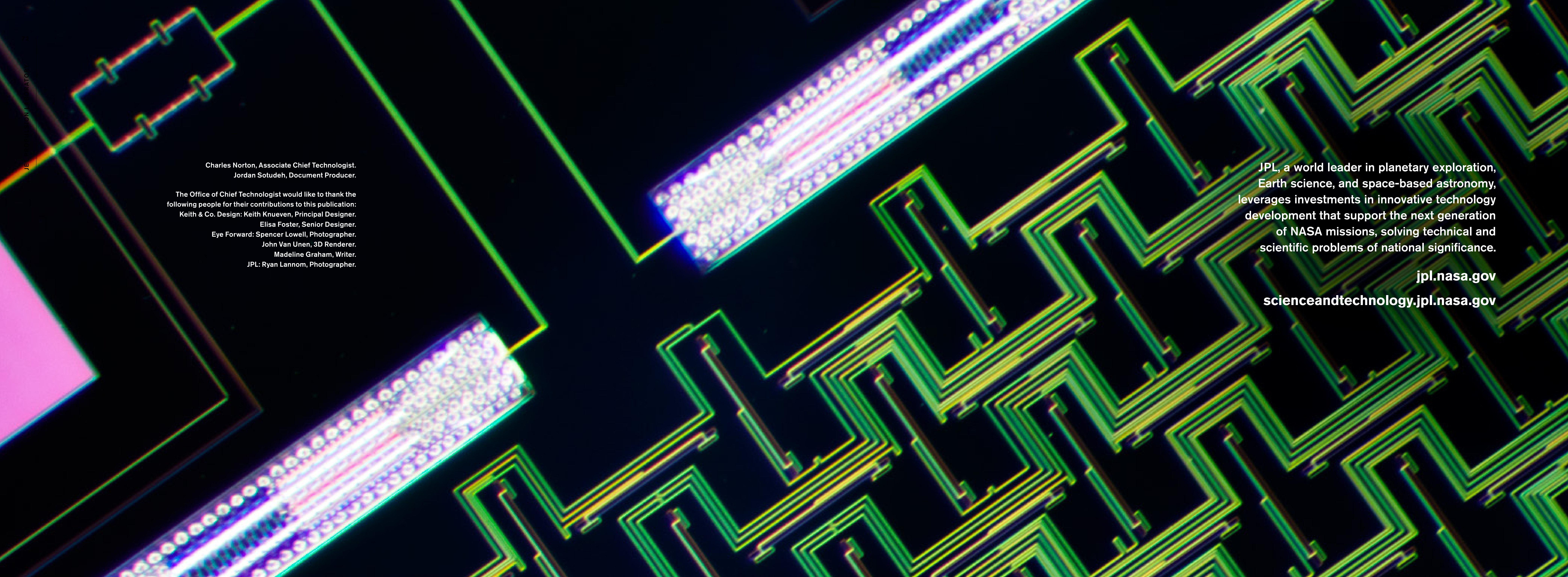
Team: Yumi Iwashita, Chris Lim, Gigi Lucena, Justin Koch, Jacqueline Sly, Scott Tepsuporn, Josh Wheeler

Acknowledgements: Michelle Gierach, Andrew Klesh







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