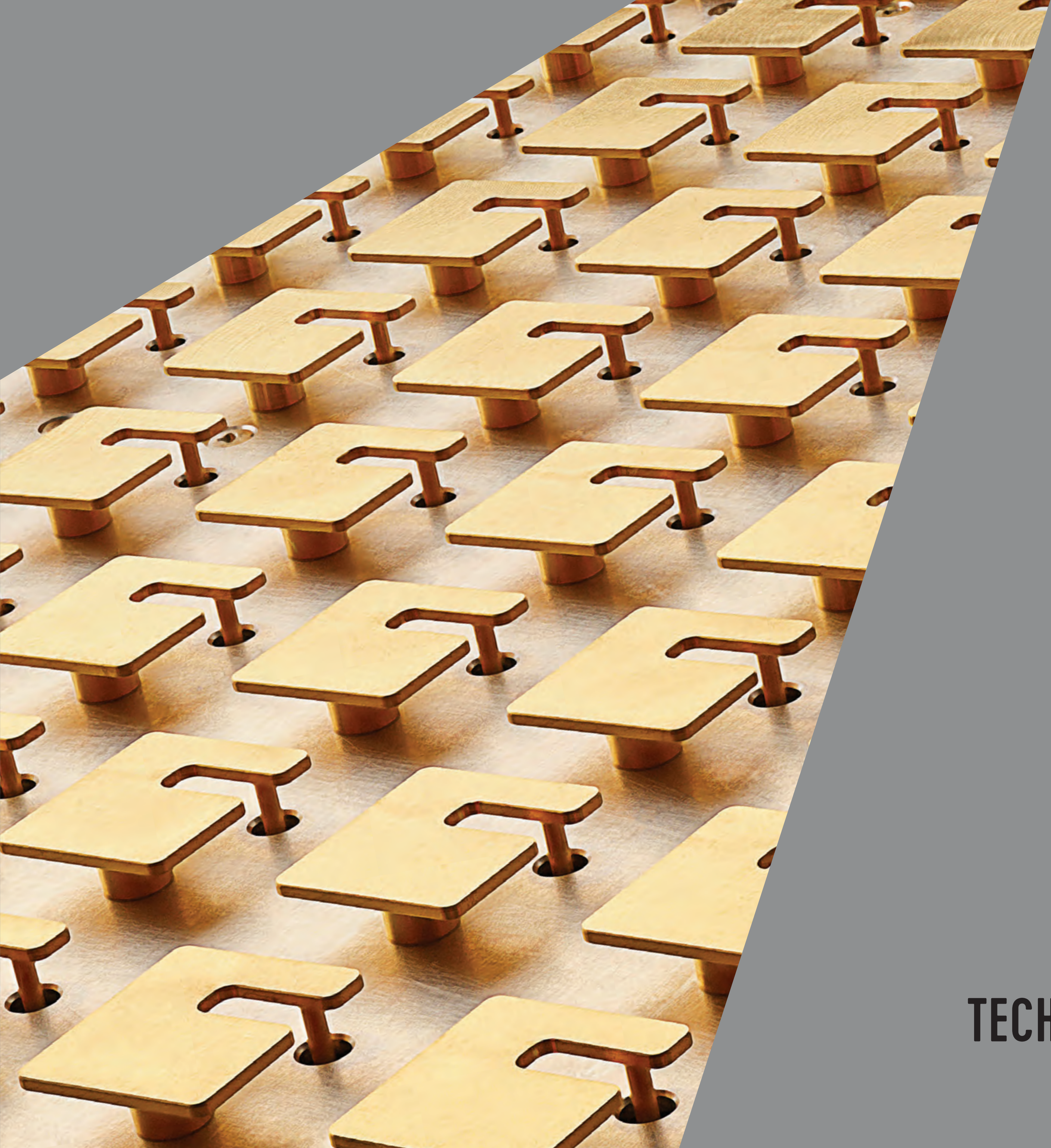


National Aeronautics and
Space Administration

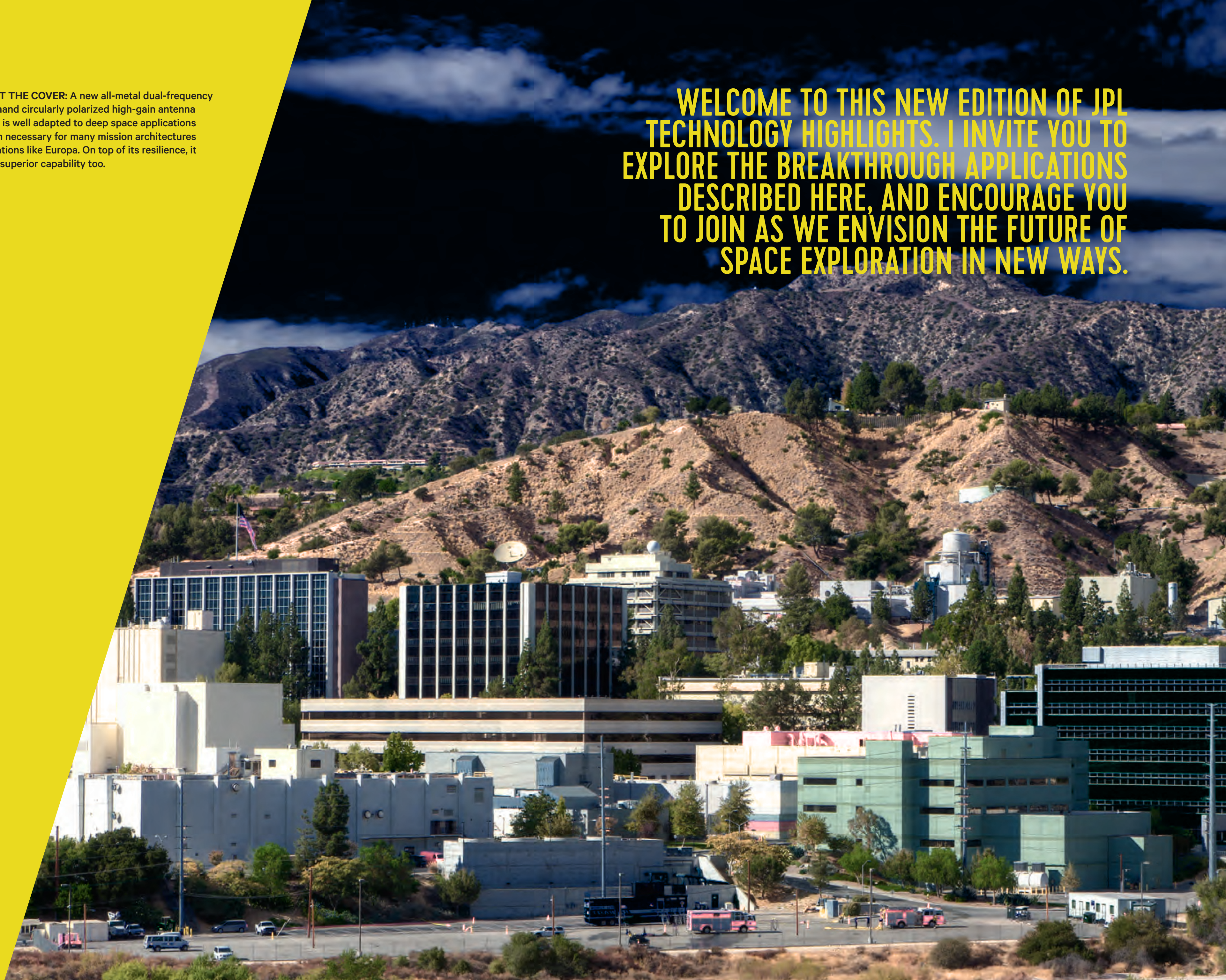
2019

TECHNOLOGY HIGHLIGHTS

JET PROPULSION LABORATORY

ABOUT THE COVER: A new all-metal dual-frequency right-hand circularly polarized high-gain antenna (HGA) is well adapted to deep space applications —even necessary for many mission architectures to locations like Europa. On top of its resilience, it offers superior capability too.

WELCOME TO THIS NEW EDITION OF JPL TECHNOLOGY HIGHLIGHTS. I INVITE YOU TO EXPLORE THE BREAKTHROUGH APPLICATIONS DESCRIBED HERE, AND ENCOURAGE YOU TO JOIN AS WE ENVISION THE FUTURE OF SPACE EXPLORATION IN NEW WAYS.



OFFICE OF THE DIRECTOR

Technology, the name we give our advanced tools, comes from the ancient Greek word ***tekhnología***, which means systematic treatment of an art, craft, or technique. At NASA's leading center for robotic exploration, we create technologies that advance the state of the art in service of our mandate: to explore space in pursuit of discoveries that benefit humanity.

JPL technologies enjoyed a very successful 2018. They traveled farther than anything humanity has made, as we were reminded when Voyager 2 passed into interstellar space. InSight landed on Mars with new technologies to learn about the planet's interior. The probe traveled with twin MarCO CubeSats fitted with a new type of antenna that allowed them to relay landing data to Earth despite their tiny scale. Earth science missions carried advanced new instruments to understand our planet, such as the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), which is making a new map of Earth's gravity every 30 days with enough accuracy to detect water underground. CubeSats complemented larger Earth science missions with more impressive capabilities than expected for their size, such as RainCube and its radar.

Prioritizing technology development and infusion has been a crucial piece of the Laboratory's mission success. Recognizing that, JPL has chosen a set of Strategic Technology Directions to focus this crucial aspect of our work. To ensure continued new achievements in our missions through 2035, JPL must lead in the following areas: autonomous systems; artificial intelligence and machine learning; data science; miniaturized systems; advanced manufacturing, design, and materials; distributed systems; communication and navigation; instruments and sensors; and robotics and mobility systems.

Every technology in this book is born from JPLers' world-class creative energy and expertise. From intelligent machines that can explore space or save lives in an emergency, to sensors capable of detecting extraterrestrial life or preventing disease, the Laboratory is building technologies that will shape our future.

I invite you to explore this year's edition of **JPL Technology Highlights**.

MIKE WATKINS
JPL DIRECTOR

OFFICE OF THE CHIEF TECHNOLOGIST

We live in a world that is increasingly defined by new technology across all walks of life. The technological landscape of our society continues to become more complex and challenging—imagine trying to drive while the roads are changing under you. To continue to operate at the cutting edge, we must pay attention to how technical applications are evolving, and use our values and experience to chart a course. Setting that course, while building in adaptability, is one of the core missions of the Office of the Chief Technologist at JPL.

The JPL Technology Highlights collection, while representing only a fraction of the impactful work taking place at JPL, showcases a wide range of technological breakthroughs: robots that can climb cliffs of ice, others that navigate above or below oceans; mobile magnetic imaging to peer through solid matter with ease; radar that can see inside clouds to predict rain; a helicopter that will fly autonomously on Mars; to increasingly powerful science missions; and instruments to detect Earth-sized worlds around other stars.

The following pages show that the technological opportunities at JPL have never been greater.

Our technologies not only reveal more of the universe's mysteries, they also offer new tools that have already changed the way humans live, work, and play on Earth—from complementary metal oxide semiconductor (CMOS) chips in phone cameras enabling modern social media, to innovative sutures used in heart surgery.

When you are going through these highlights, I hope you share my excitement when I look at all our amazing innovations today and imagine how they will fit into the future we are all helping to shape.

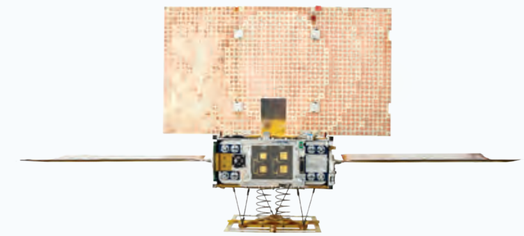
FRED HADAEGH
JPL Chief Technologist

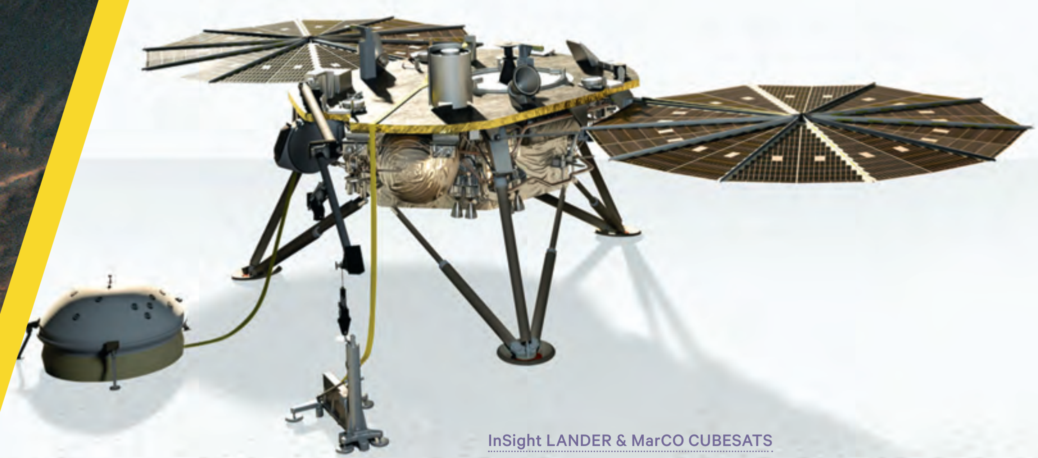
EXTRATERRESTRIAL INSIGHT

On November 26, 2018, cheers echoed through JPL Mission Control and around the world when InSight landed successfully on Mars. InSight is studying how terrestrial planets form, using Mars as a natural laboratory to study marsquakes and other geophysical activity.

The mission is conducting several scientific investigations, such as the Seismic Experiment for Interior Structure, which can detect marsquakes. While Mars does not have tectonic plates as Earth does, other processes can cause seismic movements. In addition, a self-hammering mole on the Heat Flow and Physical Properties Probe is designed to burrow below the surface to measure heat escaping from the martian interior. To help pin down the size and composition of Mars' core, the Rotation and Interior Structure Experiment precisely tracks InSight's location to determine how the Martian North Pole wobbles as it orbits the Sun.

JPL's twin Mars Cube One (MarCO) spacecraft, the first CubeSats to make an interplanetary journey, relayed to Earth the first post-landing image from InSight. Within a couple of weeks after landing, InSight had already deployed its robotic arm and placed its seismometer on the surface, taken a selfie, and achieved a remarkable planetary first: the seismometer and air pressure sensor "heard" the wind on Mars by picking up the vibration from sound waves and changes in air pressure. InSight is taking daily measurements of temperature, wind, and pressure on the Martian surface.





InSight LANDER & MarCO CUBESATS

InSight is 6 m (19.7 feet) wide, has a mass of 358 kg (789 lb.), and its robotic arm extends about 1.56 m. The twin MarCO CubeSats traveled simultaneously with, but separately from the InSight lander, and transmitted landing data back to Earth during InSight's descent through the Martian atmosphere.

TECHNOLOGY HIGHLIGHTS 2019

This JPL 2019 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 2017 and 2018, 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.

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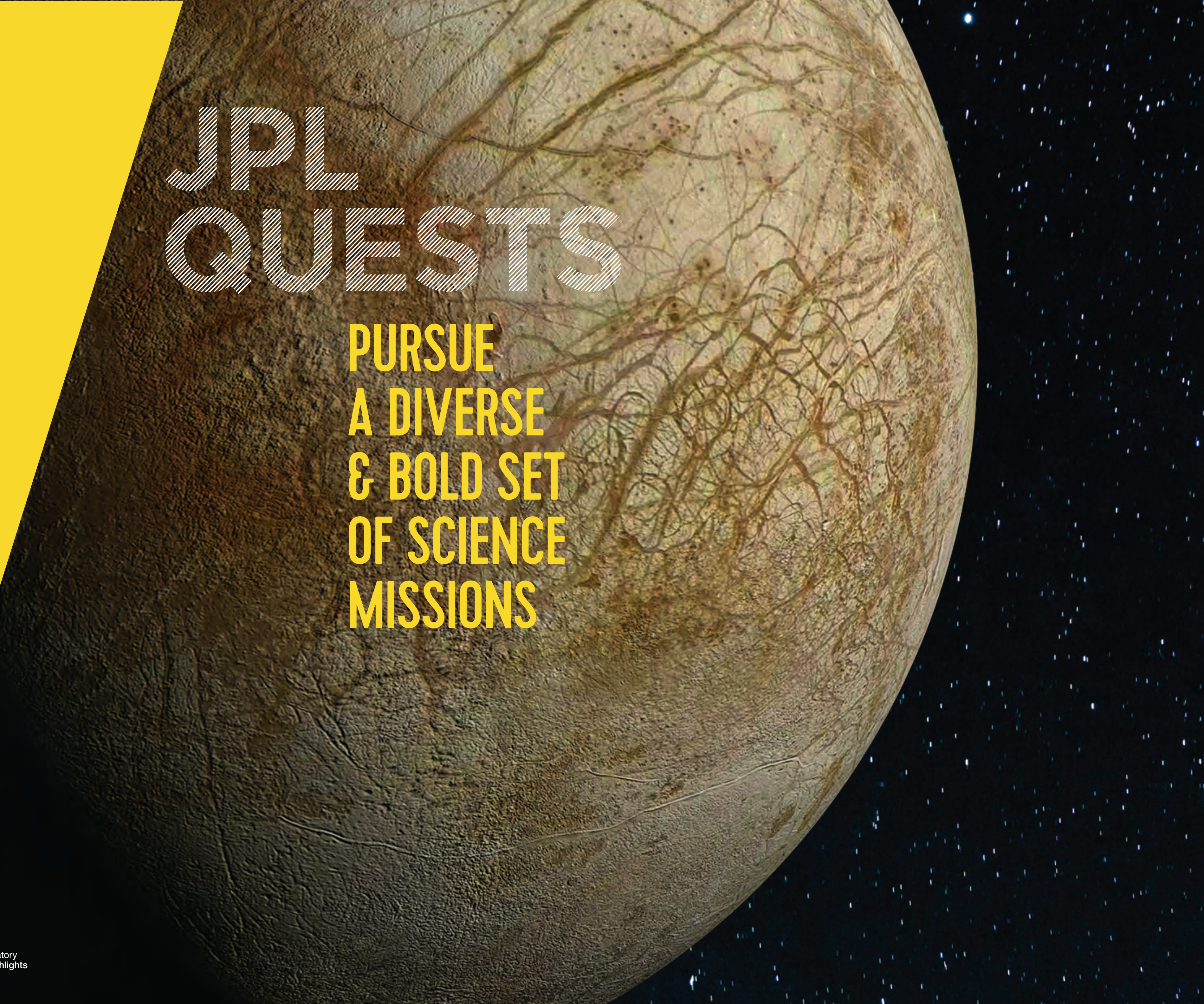
JPL QUESTS

PURSUE A DIVERSE & BOLD SET OF SCIENCE MISSIONS



01 UNDERSTAND
HOW EARTH WORKS
AS A SYSTEM AND
HOW IT IS CHANGING

02 HELP
PAVE THE WAY FOR HUMAN
EXPLORATION OF SPACE

03 UNDERSTAND
HOW OUR SOLAR SYSTEM
FORMED AND
HOW IT IS EVOLVING

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07 USE
OUR UNIQUE EXPERTISE
TO BENEFIT THE NATION
AND PLANET EARTH

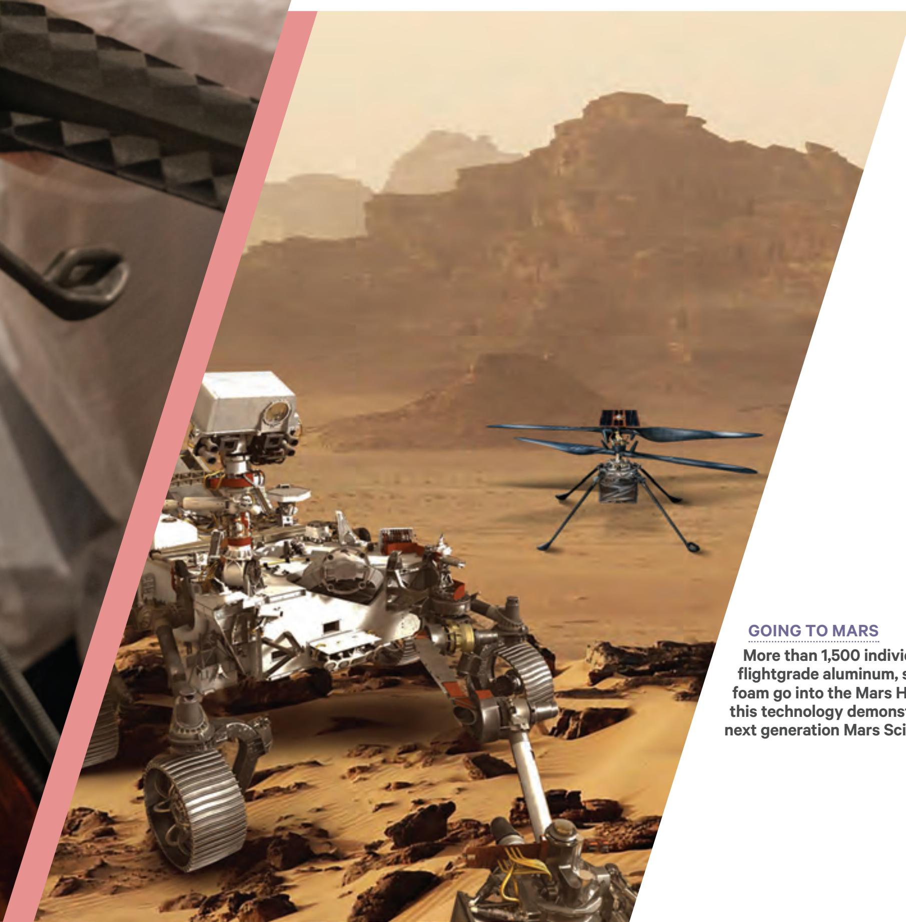
SPINNING FOR SCIENCE

FLY WHERE YOU CANNOT DRIVE

MARS HELICOPTER TEAM

Members of the Mars Helicopter team inspect the flight model (the actual vehicle going to the Red Planet), inside the Space Simulator, a 25-foot-wide (7.62-meter-wide) vacuum chamber meant to imitate extraterrestrial environments.

MARS HELICOPTER BALANCES THE NEED FOR RISK-TAKING INNOVATION AND DEMONSTRATION OF ENHANCED CAPABILITY WITHOUT ADDING RISK TO THE PRIMARY SCIENCE MISSION



GOING TO MARS

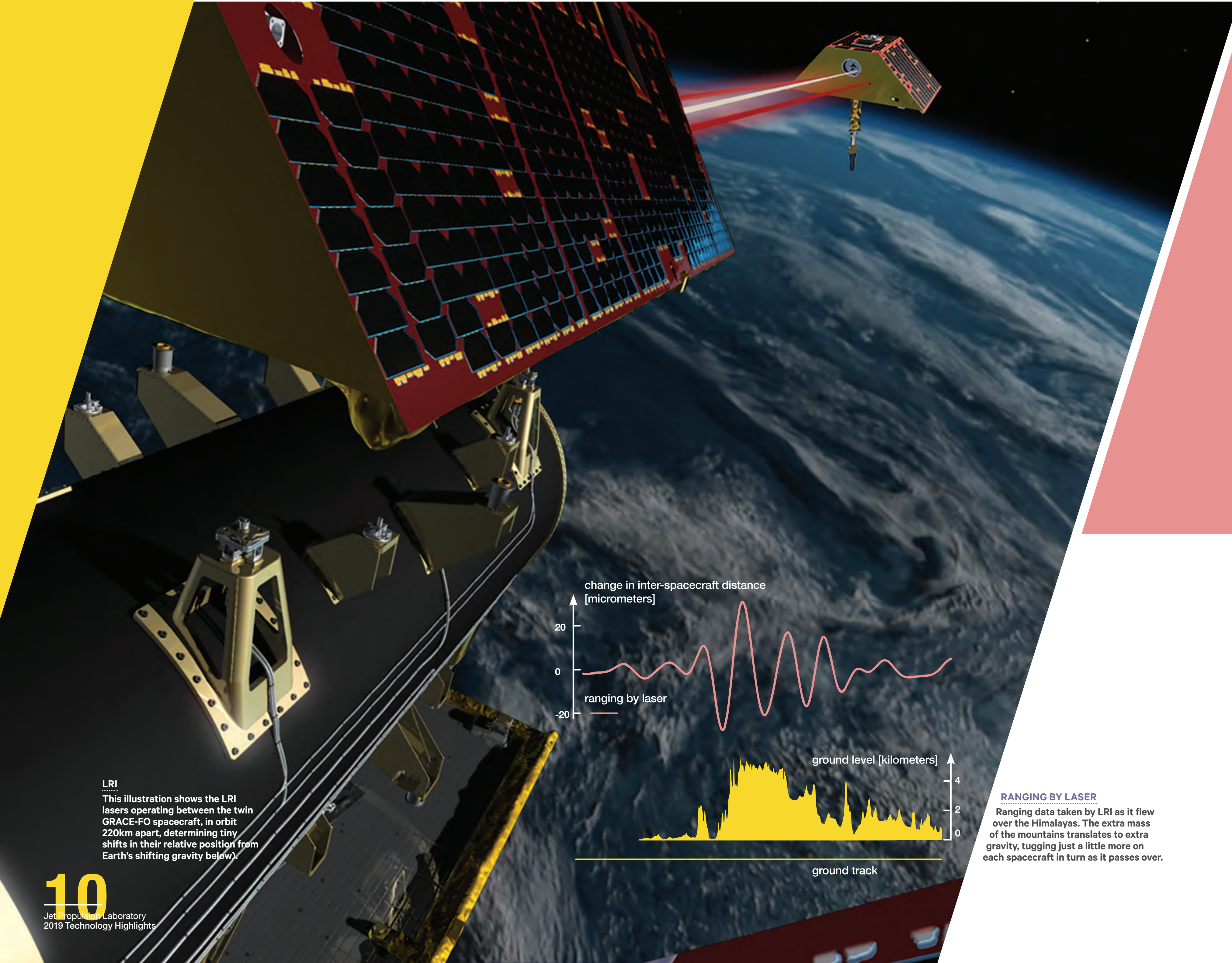
More than 1,500 individual pieces of carbon fiber, flightgrade aluminum, silicon, copper, foil and foam go into the Mars Helicopter. Experience from this technology demonstration will improve the next generation Mars Science Helicopter.

The Mars Helicopter, a small, autonomous rotorcraft, will travel under NASA's Mars 2020 rover mission to demonstrate the viability of heavier-than-air vehicles on the Red Planet. "NASA has a proud history of firsts," said NASA Administrator Jim Bridenstine. "The idea of a helicopter flying the skies of another planet is thrilling. The Mars Helicopter holds much promise for our future science, discovery, and exploration missions to Mars." This is in large part thanks to flying over obstacles, like rocks and dunes, that can be hazardous to land-based exploration platforms. Approximately 60-80 Martian days after landing, the helicopter will be released from the rover. Once the rover is about 100 meters away, it will try to fly on Mars.

The result of the team's four years of design, testing, and redesign weighs in at just under four pounds, or 1.8 kilograms. The fuselage is about the size of a softball, and its twin, counter-rotating blades will bite into the thin Martian atmosphere at almost 3,000 rpm—about 10 times the rate of a helicopter on Earth. The helicopter is optimized for Mars, from solar cells to charge its lithium-ion batteries, to a heating mechanism to keep it warm through freezing Martian nights. Mars Helicopter will also carry a camera to image the rover as it flies nearby.

Mars' atmosphere is only about 1% as dense as Earth's, so the helicopter will fly at the equivalent of 100k feet above Earth before it even takes off. The altitude record for this kind of vehicle on Earth is 40k feet. There is no pilot, and Earth will be 3–22 minutes of lightspeed travel away, but it will need to react to changing circumstances in real time. Mars Helicopter is equipped with significant autonomous capability, able to take commands from the ground, and then fly the mission without further instruction, reacting to changing circumstances in real time.

The future success of NASA missions requires both risk-averse mission execution and risk-tolerant technology development. These enhance each other, as Mars Helicopter will prove regardless of how the first flight goes. Even in the absence of complete success, the technology demonstration will give us invaluable knowledge for future planetary missions. Mars Helicopter is already driving a new paradigm of innovative mission design by prioritizing approaches to take the risks inherent in advancing technology without impacting primary mission success.



LRI
This illustration shows the LRI lasers operating between the twin GRACE-FO spacecraft, in orbit 220km apart, determining tiny shifts in their relative position from Earth's shifting gravity below).

RANGING BY LASER
Ranging data taken by LRI as it flew over the Himalayas. The extra mass of the mountains translates to extra gravity, tugging just a little more on each spacecraft in turn as it passes over.

ACHIEVING UNPRECEDENTED PRECISION WITH LASER INTERFEROMETRY

Gravity is one of the most fundamental forces in our universe. It is so powerful it can literally alter the passage of time. Multi-spacecraft observatories can use gravity to probe Earth's changing gravitational field for climatology, or the universe's most violent events–black-hole mergers–in galaxy formation.

The Gravity Recovery and Climate Experiment (GRACE), which operated from 2002-2017, was a twin spacecraft mission that led to a sea-change in gravitational science and provided the first monthly mapping of Earth's gravitational field. It was also discovered that this data could be used to detect underground water reserves–an increasingly scarce and precious commodity. The spacecraft were each in the same low-earth-orbit, but one trailed the other by 220km. The gravity signal of interest was measured by using microwaves to track the change in the spacecraft separation caused by the Earth's varying gravitational fields. Since water is the main heavy substance that can move on monthly timescales, watching the gravity map change monthly has become a new way to see the Earth's water and climate system.

The GRACE Follow-On mission (GRACE-FO) continues GRACE's important measurements, but also has a technology demonstration instrument: the Laser Ranging Interferometer (LRI). LRI is the first inter-spacecraft laser interferometer in history. The LRI uses lasers with wavelength of ~1 micron rather than the ~1cm wavelength of microwaves. The smaller wavelength means the separation measurement is significantly more precise. In practice, LRI measured the separation change of the two GRACE-FO spacecraft down to less than a nanometer, or more than two orders of magnitude more precise than the microwave system.

LRI is a collaboration led by NASA/JPL in the U.S. and the Albert Einstein Institute in Germany. The U.S. provided the laser, cavity, and laser ranging processor, while Germany provided the triple mirror assembly as well as the optical bench electronics and assembly. The LRI technology was designed to demonstrate improved performance for the next Earth Geodesy mission.

LRI can also be seen as a pathfinder for space based gravitational wave detectors, which use the same inter-spacecraft laser interferometry. The LRI lays the groundwork for missions like the Laser Interferometer Space Antenna (LISA), which plans to use laser interferometry to directly measure gravitational waves from astronomical sources. LRI is breaking new ground in applied gravitational science–giving us a deeper understanding of Earth's water and climate, and one day the astrophysics of super-massive black hole collisions.

100X MORE ACCURATE THAN ITS MICROWAVE PREDECESSOR, THE LASER RANGING INTERFEROMETER IS A WORLD FIRST—AND A PATHFINDER FOR EVEN MORE AMBITIOUS, LONG DISTANCE, DISTRIBUTED SPACE OBSERVATORIES

VANDENBERG AIR FORCE BASE

The twin GRACE-FO satellites are shown here being integrated with the multi-satellite dispenser structure that was used to deploy the satellites during launch.

POWER TO THE PUNY

LITTLE GOES A LONG WAY

PRINCIPAL INVESTIGATOR
Sona Hosseini proudly presents her miniature high-resolution spectrometer.

Our understanding—of ourselves, each other, and the universe—is limited by what we are able to perceive. During the Renaissance, Galileo's telescopes allowed us to see a new reality—one that had been impossible to know until then. Today, the technologies we use for seeing are more than lenses; they also cut and reconfigure beams of light to improve image quality, use software to piece things together—frequently this requires huge installations to push the boundaries of image resolution, i.e., what we can see in the universe. Of course, we observe more than just the visible range: discoveries remaking how we understand the shape and nature of our universe, just like Galileo's, are coming from ultraviolet, infrared, X-ray, and other wavelengths of light.

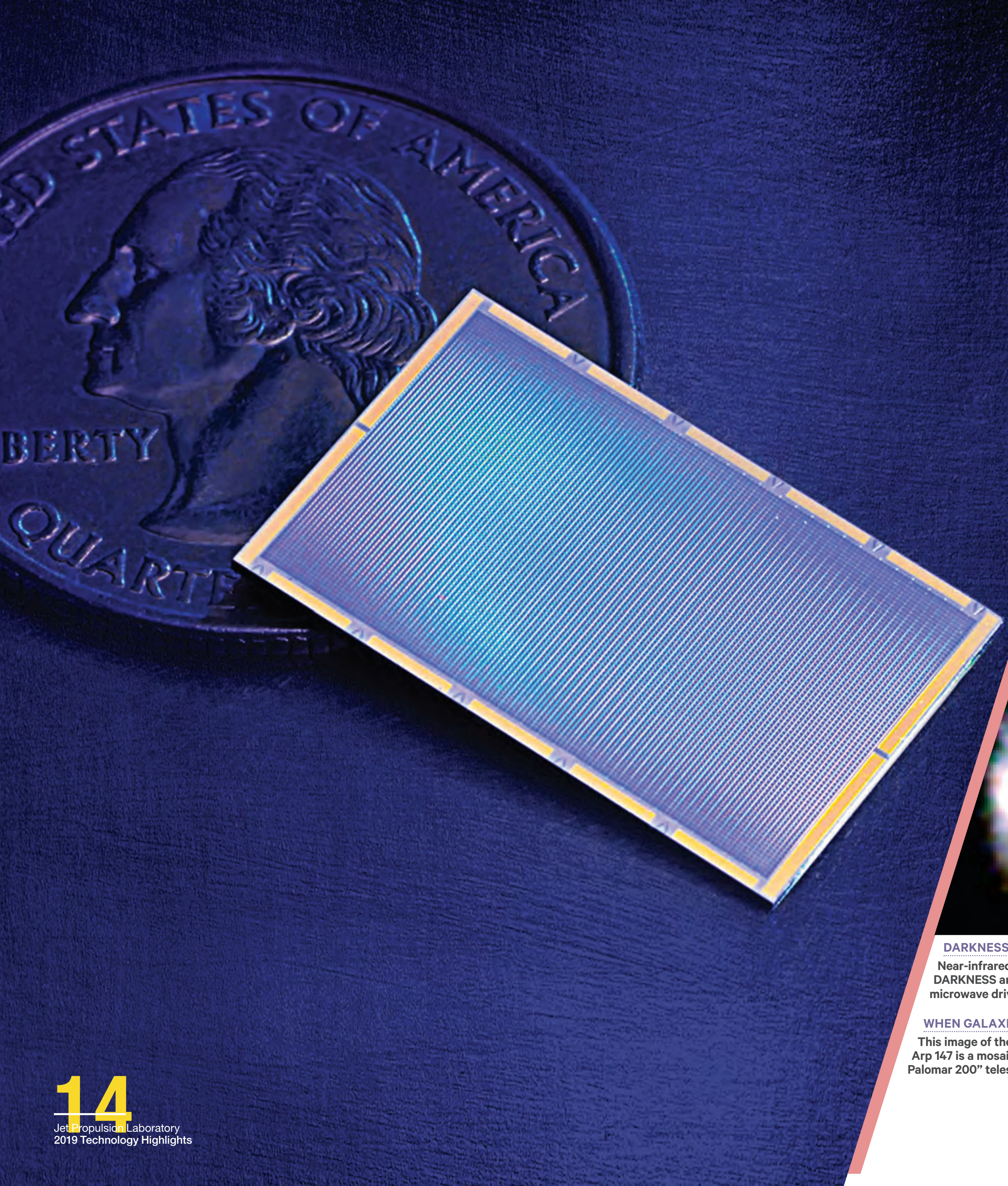
Technologists have developed a spectrometer to leverage these technology trends in optical sciences. Many of NASA's future key scientific goals will become achievable with the benefits of the next generation of miniature high-resolution spectrometers. The JPL mini high-res spectrometer is about the size of a thumb, obtains high spectral resolution with no moving parts, and requires very small input optics. It can observe weak targeted atomic and molecular spectral lines at these high resolutions thanks to a novel interferometric capability known as a spatial heterodyne spectrometer.

Employing this technology, future platforms will see fainter signals with higher sensitivity to detect and analyze important volatiles such as water in a comet, lunar environment, or anywhere else. Having the capability to detect isotopic ratios in the water tell us about its source, and ultimately where the water on Earth came from. High-sensitivity miniature sensors onboard multiple, small autonomous platforms, with each dedicated to a different wavelength, would enable a leap forward for future space explorations.

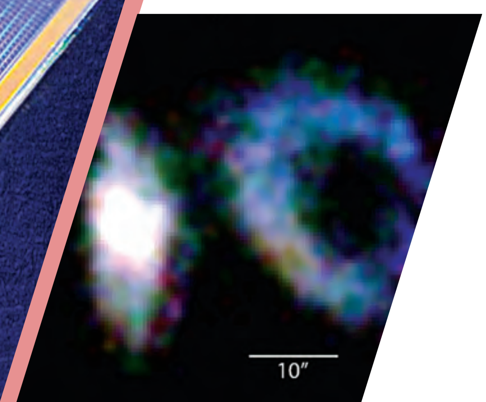
Coming back down to Earth, the next generation miniature high-resolution spectrometer can provide unprecedented spectral markers, with many applications to everyday life. For example, it could provide a fingerprint to identify targeted atoms and molecules in medicine, authentication and gas analyzers to identify active pharmaceutical ingredients, or in real-time monitoring of anesthetic and respiratory gas mixtures in combat fields or during medical surgeries. The technology also opens the door to personalized medicine, like scanning eyes or blood. And thanks to the spectrometer's small size, all these capabilities could be accessed from a small, hand-held device, like a phone.

USING A NEW CAPABILITY, SPATIAL HETERODYNE SPECTROMETERS, FAR SMALLER—AND IN MANY WAYS MORE CAPABLE—SENSORS ARE NOW AVAILABLE FOR USE IN SPACE, WITH MYRIAD APPLICATIONS HERE ON EARTH

BIG THINGS COME IN SMALL PACKAGES
This miniaturized system could lead to unprecedented amounts of science return on mission investment, whether by freeing up mass in one system, or enabling a distributed network of small sensors.



TAKE A CLOSER LOOK AT OUR COSMIC NEIGHBORHOOD



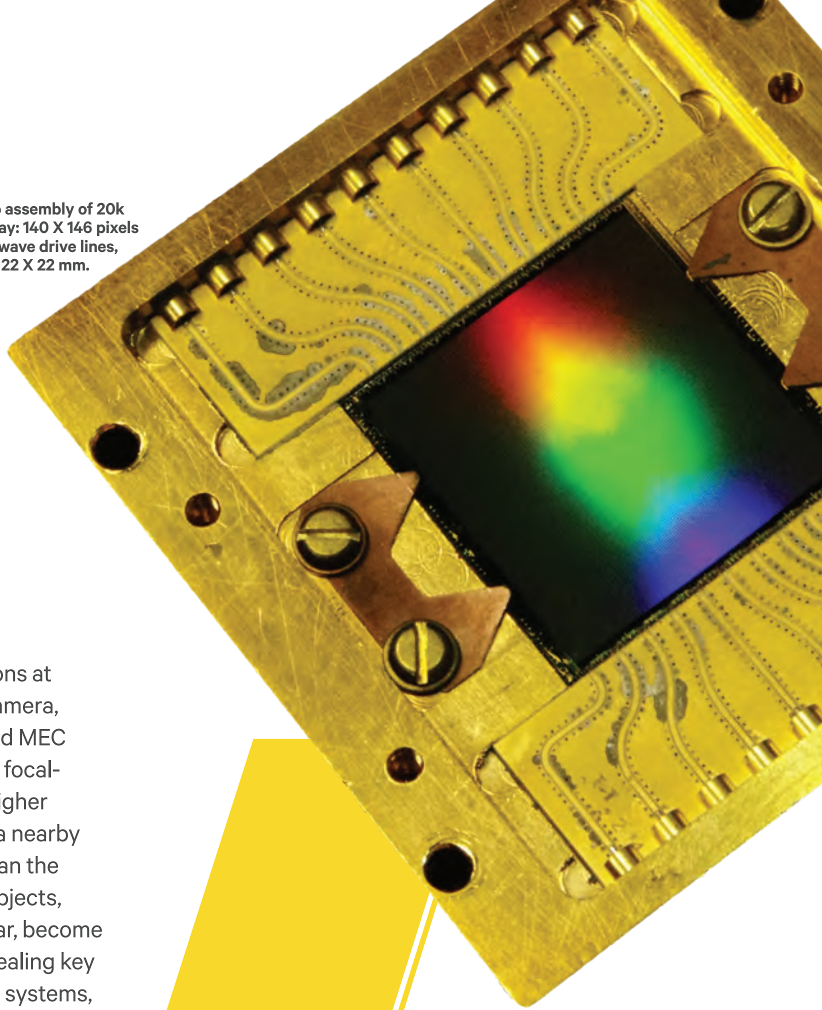
DARKNESS

Near-infrared detector chip of 10K pixel DARKNESS array: 80 X 125 pixels with 5 microwave drive lines and a quarter for scale.

WHEN GALAXIES COLLIDE

This image of the interacting galaxies Arp 147 is a mosaic from ARCONS on the Palomar 200" telescope.

LIGHT THROUGH DARKNESS



MEC ARRAY

Mounted chip assembly of 20k pixel MEC array: 140 X 146 pixels with 10 microwave drive lines, 150 um pitch, 22 X 22 mm.

We used to wonder if the stars we see at night had any planets at all. Today, based on thousands of observed exoplanets, it is believed that on average, several planets orbit every star in the galaxy. We "see" them indirectly, by measuring changes in starlight and gravity that occur when the planet passes between us and its parent star. Newly developed technology will tell us what those planets are made of.

Researchers at JPL's Microdevices Laboratory (MDL) developed and fabricated advanced ultraviolet-optical-near infrared (UVOIR) microwave kinetic inductor detector (MKID) arrays, which can work with large telescopes and an adaptive optics system to enable direct imaging of faint exoplanets around nearby stars.

MKIDs use superconducting material to enable simultaneous single photon—the smallest measurable element of light—counting and energy resolving capabilities. Each pixel is composed of a tuned inductor-capacitor resonator, and up to 2000 such pixels are coupled to a single microwave transmission line. This multiplexing technique simplifies wiring and reduces the heat load of science instruments that must be operated at cryogenic temperatures. The primary advantages of MKIDs over conventional detectors are the absence of read noise and dark current, which represent the scatter of its readings, and a fast readout time, the equivalent of several thousand frames per second. These capabilities have no analog in present semiconductor-based detectors. The key technical advance is in production: novel materials are deposited on substrates and patterned to form integrated circuits, improving the spectral response and quantum efficiency of photon detectors.

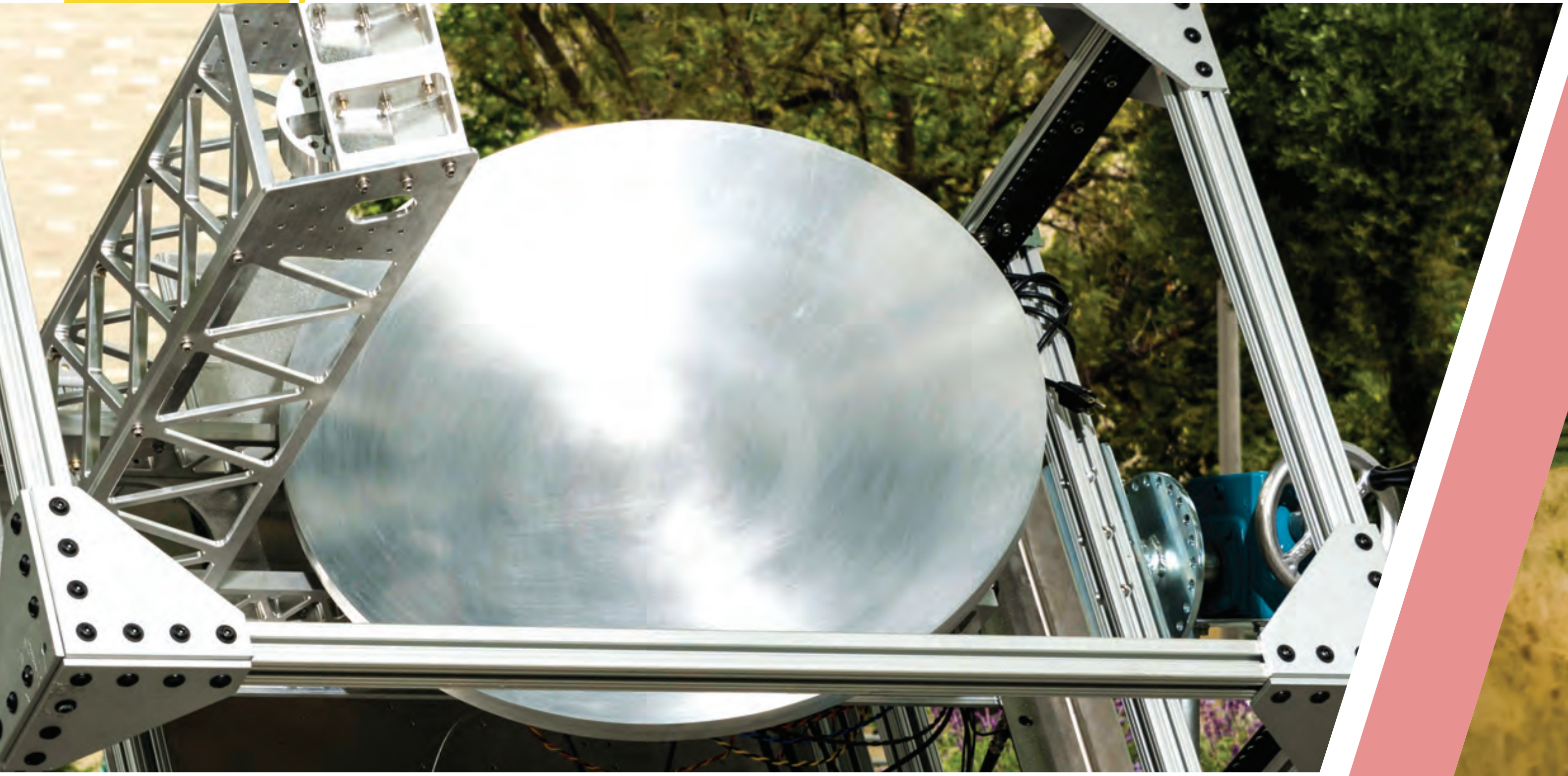
JPL delivered 2k pixel UVOIR MKID arrays for the Claude mount at Palomar (Array Camera for Optical to Near-IR Spectrophotometry, aka ARCON), 10k pixel devices for the Cassegrain mount at Palomar (DARK-speckle Near-infrared Energy-resolved Superconducting Spectrophotometer, aka DARKNESS) and most recently, 20k pixel devices for exoplanet observations at the Subaru telescope (MKID Exoplanet Camera, aka MEC). In particular, the DARKNESS and MEC cameras act as both science cameras and focal-plane wavefront sensors, which enables higher contrast ratios between a bright star and a nearby faint exoplanet. Higher contrast ratios mean the changes in light caused by even smaller objects, such as an Earth-like planet passing its star, become noticeable. This technology is already revealing key characteristics about planets in other star systems, like mass, distance, orbital period, and chemical signatures.

ADVANCED PHOTON DETECTORS CAN DETECT THE CHEMICAL COMPOSITION OF PLANETS AROUND NEARBY STARS FROM EARTH

CLOUD UNCOVER

VAPOR IN-CLOUD PROFILING RADAR

VIPR is a low-power 170 GHz radar system capable of measuring water vapor profiles inside of clouds. Radar echoes from clouds and the ground, when processed correctly, can be used to determine absolute humidity content.



VIPR WILL IMPROVE OUR UNDERSTANDING OF RAIN AND THE WATER CYCLE

VAPOR-IN-CLOUD-PROFILING RADAR (VIPR) WILL SHOW US WHAT HAPPENS INSIDE CLOUDS

Water vapor is a major source of uncertainty in atmospheric modeling—models that help us plan for significant changes in weather, including hurricane prediction. The ability to directly measure humidity inside of clouds is key to our understanding and preparation for weather. Clouds often confuse today's sensor systems, such as differential absorption lidar. Vapor In-Cloud Profiling Radar (VIPR) is the world's first range-resolving atmospheric absorption radar —a differential absorption radar—that can measure humidity directly inside clouds. This was previously impossible to do remotely due to limitations in the ability of other methods to reliably and accurately sense inside clouds at all levels of the atmosphere.

Innovations include world-record signal source efficiency/power when tuned near 170 GHz by using solid-state transmitters, specialized low-noise amplifiers and a quasi-optical design for high-sensitivity detection, software for signal processing and extracting the humidity data out of the signal, and mechanical design and aircraft-readiness preparation for VIPR's test flights at the end of 2019.

VIPR provides significant power efficiency over previously flown radar. It offers 500 mW of transmit power over 167–175 GHz thanks to a novel 'Schottky diode' based device, designed and fabricated in-house at the Microdevices Laboratory. VIPR's sensitive receiver also uses a specially designed mixer and low-noise amplifier designed in-house and fabricated by Northrop Grumman. VIPR's radar architecture and operation was developed by a close collaboration between radar engineers and climate scientists.

WHAT CLOUDS REALLY LOOK LIKE

VIPR addresses the NASA Earth Science goal of providing high resolution water vapor profiles in Earth's clouds.

In 2018, VIPR's final radiofrequency and optical builds were completed. Its ability to accurately retrieve humidity measurements inside clouds and rain was validated in ground testing and on balloons launched by collaborators at the Scripps Institute of Oceanography. VIPR shows promise in finally giving us the ability to uncover the true nature of clouds.

Differential absorption radar similar to VIPR but adapted to different needs can be used more broadly in a variety of atmospheric contexts on Earth. These include remote sensing of water vapor emitted by volcanoes or at high altitudes, and measuring oxygen abundance to also extract temperature and pressure data about the atmosphere. Beyond Earth, differential absorption radar based on the VIPR architecture would be an effective tool for measuring trace water vapor on Mars or over icy moons of the outer planets. Finally, VIPR's advanced millimeter-wave technology can be used for a variety of civil and national security applications including both radar and communication systems where very short wavelengths offer both high spatial resolution (can detect smaller things) and high bandwidth. /

TECHNOLOGY TO FIND OUR FIRST HOME AWAY FROM HOME

PARSING PARVI
Principal Investigator Gautam Vasisht adjusts optical components during a live technology demonstration. Radial velocity measurements find exoplanets by looking for changes in the light from a star caused by the small but detectable tug of planets in its orbit.

TERRA NOVA

Before the first exoplanet was discovered, in 1992, scientists debated whether other stars had planets at all. Today, with over 4000 exoplanets confirmed, exoplanet research is one of the most exciting fields in astronomy. A major driver of that excitement is the very real prospect that in the near future we will finally know another planet we could live on. A total of 50 of the 63 stars within 5 parsecs, or 16.3 lightyears, of Earth are red dwarfs. These smaller stars emit relatively more infrared light, driving the need for infrared spectrographs.

The Palomar Radial Velocity Instrument (PARVI) is the first ever adaptive optics fed, diffraction-limited spectrograph on sky. Commissioned at the Palomar Hale Telescope in June 2019, PARVI will search for planets orbiting nearby low-mass stars, measure how fast they orbit, and use that data to infer the mass of the planet. PARVI will look for a few "hot Jupiters," or gas giants with very short orbits, orbiting near young stars. Its main focus however is on small, rocky, planets in the habitable zone of low-mass stars. In some ways, it is much easier to detect Earth-like planets around low-mass stars, because the planet is bigger relative to the star, and because a less bright, less hot star's habitable zone is closer to it.

Previously, infrared technology faced several optomechanical hurdles, and their suitability for radial velocity measurements at the sub-m/s level had not been demonstrated. PARVI has solved the technical issues of operating in the infrared, couples light from two infrared bands, can be used with extreme-adaptive optics systems, and is expected to measure radial velocity as accurately as 0.5 m/s. PARVI is also about 300 times smaller in volume than instruments of similar resolving power on similarly sized telescopes. Size savings are one reason PARVI serves as a technology model for high-resolving power spectrographs for space missions as well as extremely large telescopes.

This technology will also complement future missions for more refined exoplanet detection. EarthFinder, for example, is a precise radial velocity probe mission concept for the detection of Earth-mass planets orbiting Sun-like stars. This would give us our best chance at finding another planet like Earth orbiting a star like our Sun. Few discoveries would match the impact of finding another Earth in our corner of the galaxy.

THOUSANDS OF WORLDS HAVE BEEN FOUND AROUND OTHER STARS—NEW DETECTOR TECHNOLOGY IS NEEDED TO TELL IF ANY NEARBY CAN SUPPORT LIFE AS WE KNOW IT

HOT JUPITERS

The PARVI data below is on "hot Jupiters" or gas giants with orbits very close to their parent-star. PARVI is also searching for worlds in the habitable zone of smaller, nearby stars.

BOTS OF BURDEN

The Llama quadruped robot, weighing in at 75 kg / 165 lbs., can walk in any direction, almost as fast as a human. Its nominal walking speed is half a meter per second in all directions, with a top speed of 0.8–1 meter per second in a forward direction; the human equivalent is about 1.2 meters per second. With its speed and mobility, this prototype has broad applications, particularly in environments with rough, uneven terrain, and in situations not suitable for traditional robots that use wheels or tracks to move. Llama can also carry things while keeping up with its human partners, and can stand in for people in high-risk scenarios involving security, disaster response, or space operations.

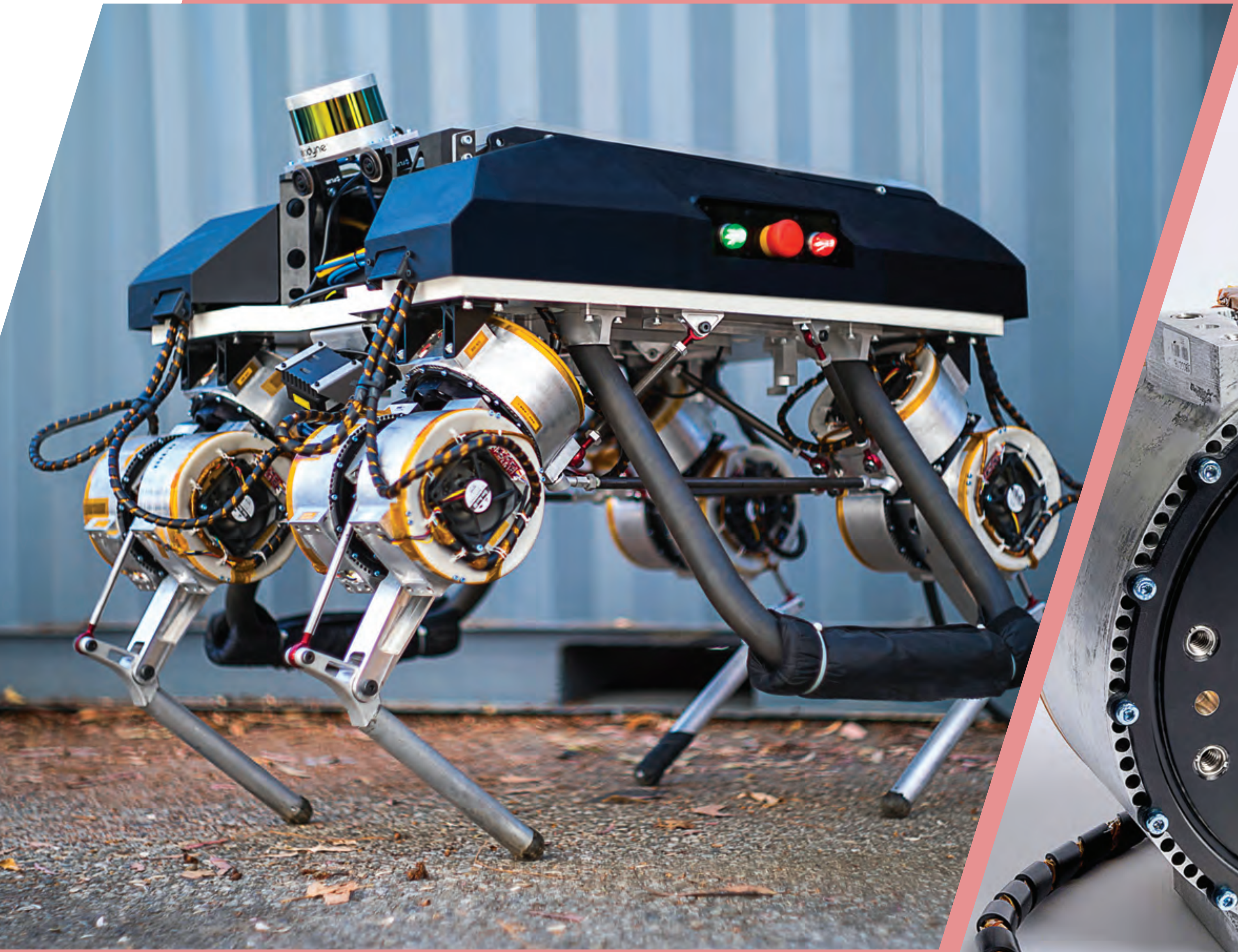
One of Llama's key enabling technologies is the actuator design. An actuator is a mechanism that makes something, in this case legs, move. With traditional robots, there is a fundamental tradeoff between speed and torque—that is, the faster the robot can move, the less it can carry, and vice versa. Traditional actuators use mechanical springs with highly geared motors to manage the sharp impacts experienced in movement. However, Llama uses custom actuators with low gear ratios and no mechanical springs. These new actuators provide excellent torque performance at high speed and are designed to be modular, or adjustable.

In Llama's design, twelve identical actuators are used in a quadrupedal configuration: four legs with three actuators per leg. The actuator technology enables control algorithms to adjust leg stiffness on the fly. This lets Llama adapt to changing off-road conditions, and a wider range of unforeseen terrain conditions than traditional robots. These payload optimized actuators also allow onboard computing and sensing. Llama has two onboard computers, one for control and one for perception, and a robust sensor suite to operate autonomously.

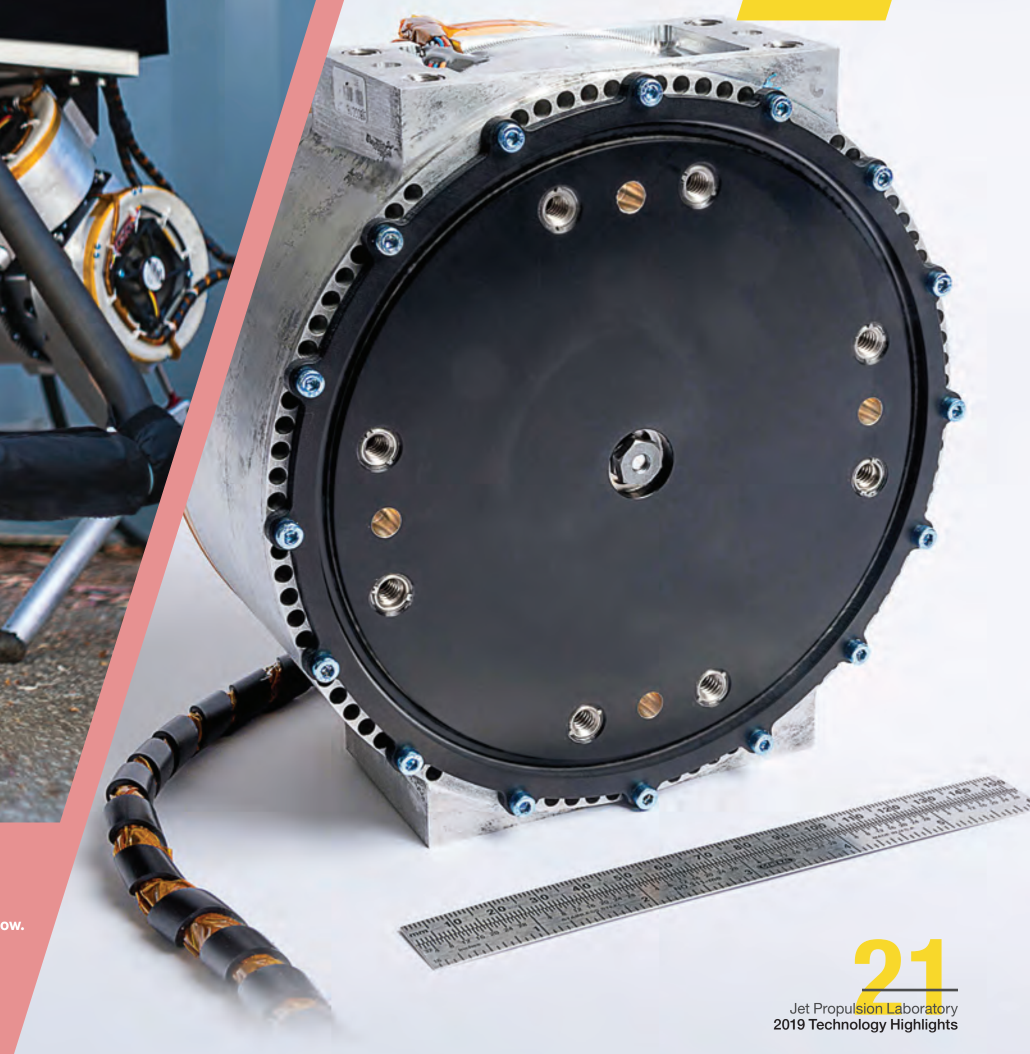
The sensor suite consists of a customized large-field-of-view-stereo pair, a three-dimensional lidar for far-field assessment, and a scanning two-dimensional lidar for near-field terrain assessment.

In 2018, the Llama team designed, developed, tested, and delivered a prototype within eight months, with integration and testing carried out in JPL's Mobile Manipulation Lab. JPL designed and integrated the custom actuators, developed a custom power system, and assembled and tested the entire robot from scratch. Although the bulk of the development work was done at the Laboratory, there were contributions from a large number of private and public groups, including motor companies, machine shops, and other research institutions. Based on lessons learned from the first version of the robot, the team is now developing a second prototype for 2019.

LLAMA IS A NEWLY DEVELOPED, DYNAMIC, OMNIDIRECTIONAL, QUADRUPED ROBOT



IN DISASTER ZONES, LIVES DEPEND ON OUR ABILITY TO REACH THEM IN TIME; WHEN HUMAN RESCUE TEAMS FACE RADIATION OR OTHER SERIOUS HAZARDS, MACHINES ARE NEEDED

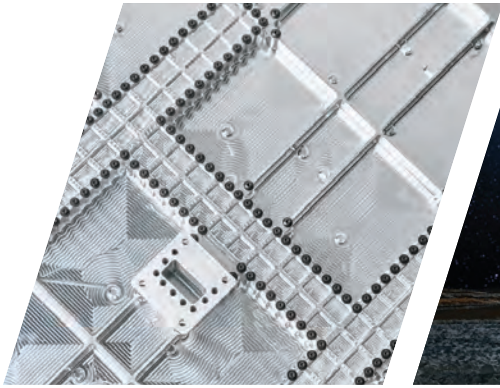


LLAMA ROBOT
The first Llama prototype, pictured here, is already being improved upon in the second version of the Llama robot. A mechanical pack animal with programmable intelligence would benefit all kinds of field operations.

ELECTRIC ACTUATOR
This custom large diameter electric actuator enables dynamic behaviors, such as suddenly applying less pressure to a footstep when sensing unsafe terrain below.

THIS INNOVATIVE ANTENNA DESIGN IS A SOLUTION FOR RETURNING SCIENCE FROM HOSTILE ENVIRONMENTS AND VAST DISTANCES

NOT EVEN EXPERTS THOUGHT THIS DESIGN WAS FEASIBLE



CLOSE-UP

Waveguide power divider feeding the antenna subarrays. These are embedded into the structure of the antenna to enable more input power.

DESTINATION EUROPA

A new all-metal dual-frequency right-hand circularly polarized high-gain antenna (HGA) is well adapted to deep space applications —even necessary for many mission architectures to locations like Europa. On top of its resilience, it offers superior capability too.

Getting 33kbps science data return from ¾ of a billion miles away requires antennas more efficient than anything anyone has ever flown. Traditional mission design with previous state-of-the-art technology would require either an additional spacecraft to relay communications from Jupiter to Earth, or would require a large, high gain antenna. Existing low-profile antenna designs cannot survive because of cryogenic temperatures and radiation levels on the surface of Europa: extreme radiation gets trapped in Jupiter's magnetic field, bombarding anything inside with intense amounts of dangerous particles that fry most electronics, while surface temperatures on Europa range from –260 to –370 °F (–160 to –220 °C), devastating most materials antennas have ever been made of.

Technologists have prototyped a radical antenna design to establish a direct-to-Earth two-way radio link from destinations nearly a billion miles away, like Jupiter's moon, Europa. This icy moon has become a destination of major interest for many scientists, as Europa is believed to have all the building blocks for life as we know it. Scientists even think the ocean underneath Europa's dense, icy crust may contain life.

Because of extreme temperatures, radiation, and very limited physical space, the design was adapted: a flat, metal antenna. Their key innovation in achieving this, is a circularly-polarized metal-only element. The design also mitigates electrostatic discharge—static electricity that can destroy any active sensors, components, or other systems onboard. The antenna is made of 4×4 subarrays, each consisting of 8×8 patch arrays. The subarrays are fed using a 1:16 waveguide power divider; by embedding this, the antenna can handle much more input power. In fact, the first prototype demonstrated over 80% efficiency on X-band transmission and reception, survived high energy proton bombardment, and temperatures as cold as –170 °C.

The new technology was rapidly matured from a Technology Readiness Level of 1 up to 5 within a year. This technology can easily be adapted to other frequency bands used for planetary missions and other mission environments. It could increase data return from Mars eight-fold without impacting antenna weight or size, and eliminate the need for auxiliary spacecraft to relay lander communications as we expand exploration to new planets. By going after the hardest challenges, we make the impossible just difficult.

SENSE & SENSABILITY

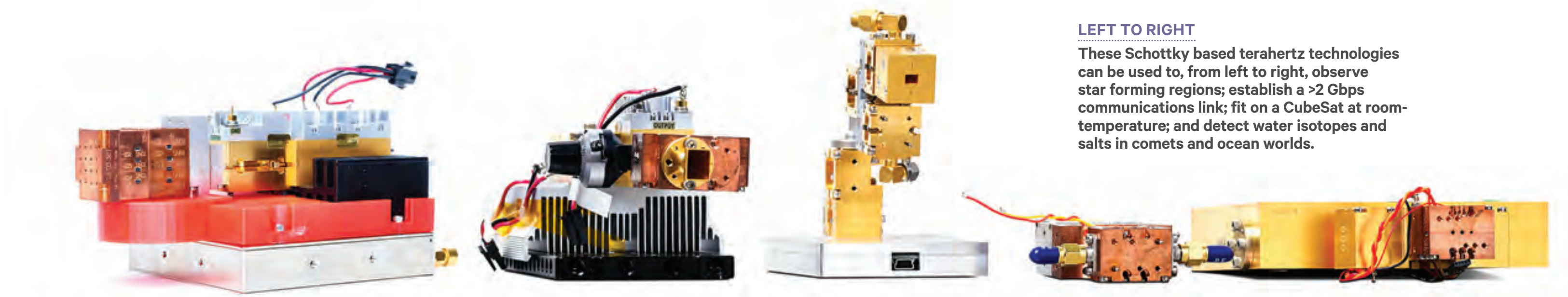
NOVEL TERAHERTZ SOURCES AND RECEIVERS ARE SENSITIVE ENOUGH TO DETECT SEVERAL SIGNATURES AT ONCE, WORK WITHOUT CRYOGENIC COOLING, AND USE 10 TIMES LESS SIZE AND POWER THAN ALTERNATIVES

Much of the universe is not only unknown but unseeable to our eyes. Sensors can show us the universe through light's "invisible" frequencies, like X-rays, ultraviolet, and infrared. At the end of the infrared frequency, up to microwaves, is a range known as the "terahertz gap" because of our inability to reliably sense what lies within it. Scientists are interested in the terahertz gap because it can show us how stars and galaxies formed, as well as detect organic molecules, water, and minerals like salt. Until now, size, power, and temperature requirements prevented an effective solution.

New terahertz sources and high-spectral resolution receivers are addressing the terahertz gap. A thorough redesign of these devices has improved efficiency and power output up to ten times over using a novel JPL-patented circuit design called "on-chip power-combining." A second novel technique, "on-chip frequency diplexing," has doubled frequency bandwidth—up to 50% radiofrequency bandwidth.

The high-spectral resolution (>106) also allows multiple targets in the same line of sight. Combined, these techniques enable, for the first time ever, simultaneous measuring of organics, salts and water isotopes for mapping comets and ocean worlds (210-600 gigahertz), or key tracers of star forming regions (1.4-2.7 terahertz). Terahertz sources, receivers and radars also contribute to understanding the Earth, in everything from cloud humidity, to ozone and carbon dioxide measurements.

Available technology would need several much larger instruments with dedicated temperature controls to achieve this capability. The high frequency of the terahertz range means that the two key components of the receiver, the local oscillator and mixers, must be micron-sized (a human hair is about 200 microns wide). Before the innovative techniques described here, limitations in semiconductor properties made it almost impossible to achieve the output power at the size and temperature which was demonstrated this year.



LEFT TO RIGHT

These Schottky based terahertz technologies can be used to, from left to right, observe star forming regions; establish a >2 Gbps communications link; fit on a CubeSat at room-temperature; and detect water isotopes and salts in comets and ocean worlds.

The high power need, extremely cold operating temperature, and size requirements were until now, major bottlenecks to reaching this range of signals.

The terahertz range is of interest for more than science, and has application in security, such as in remote detection of concealed weapons, and for terahertz communications to provide rural areas in the US with ultra-fast wireless connectivity. JPL has also started a collaboration with the National Institutes of Health (NIH) to integrate these new terahertz sources in novel micro-MRI (magnetic nuclear resonance) systems developed at the NIH. This would demonstrate the first ever sub-cellular resolution MRI system. If successful, this will be a major breakthrough in medicine–seeing inside cells will provide invaluable information on how most pathologies proliferate in their very early stages and develop into disease. This could help chart new paths to developing cures, and to develop them faster in combatting new diseases.

NEW EYES TO SEE THE UNSEEN UNIVERSE: FROM GALAXY FORMATION TO THE INSIDE OF A SINGLE CELL

SENSING BIG & SMALL

Hubble Space Telescope image of the Carina nebula, left, and illustration of brain cells, right. The terahertz technologies featured can be used to obtain high-resolution maps of star forming regions like the Carina nebula at unprecedented speeds, and provide a detailed "MRI" of microscopic organics like viruses and human cells.

LESS SIZE, WEIGHT, AND POWER, FOR MORE CAPABILITY

Current instrument systems are too large, heavy, and power hungry for small satellites like CubeSats or on deep space missions where space and power is more limited. Space missions must account for limited space, weight, and power on a spacecraft —so much so, they use the acronym "SWaP" for size, weight, and power. Currently, smallsats provide faster and cheaper production at the expense of higher quality capabilities. Advances in miniaturization of instruments, however, will change the equation for space missions by providing the same capability on much smaller satellites.

Weighing only 100 grams and using just 0.5 W of power, this spectrometer offers up to 15 times more power savings and 20 times more size and mass savings than previously flown technology, as well as significant cost savings. This technology provides data collection speeds previously too demanding for small, inexpensive satellites, or deep space missions. The new spectrometer, developed in partnership with the University of California, Los Angeles, operates at 180 GHz and 550 GHz, and is designed to measure stratospheric water. It takes microwaves in and breaks them down into their spectral components before digitizing the signal as a function of a wavelength. According to how they are tuned, spectrometers can detect different chemical components in an object based on what it detects from the waves that object emits or reflects.

This breakthrough spectrometer can be used to study other planets—in particular, off-world water, such as in the plumes jetting out of Saturn's moon Enceladus—and to analyze the composition of comets. In addition, the technology can be applied to Earth science, where it can help advance our understanding of weather.

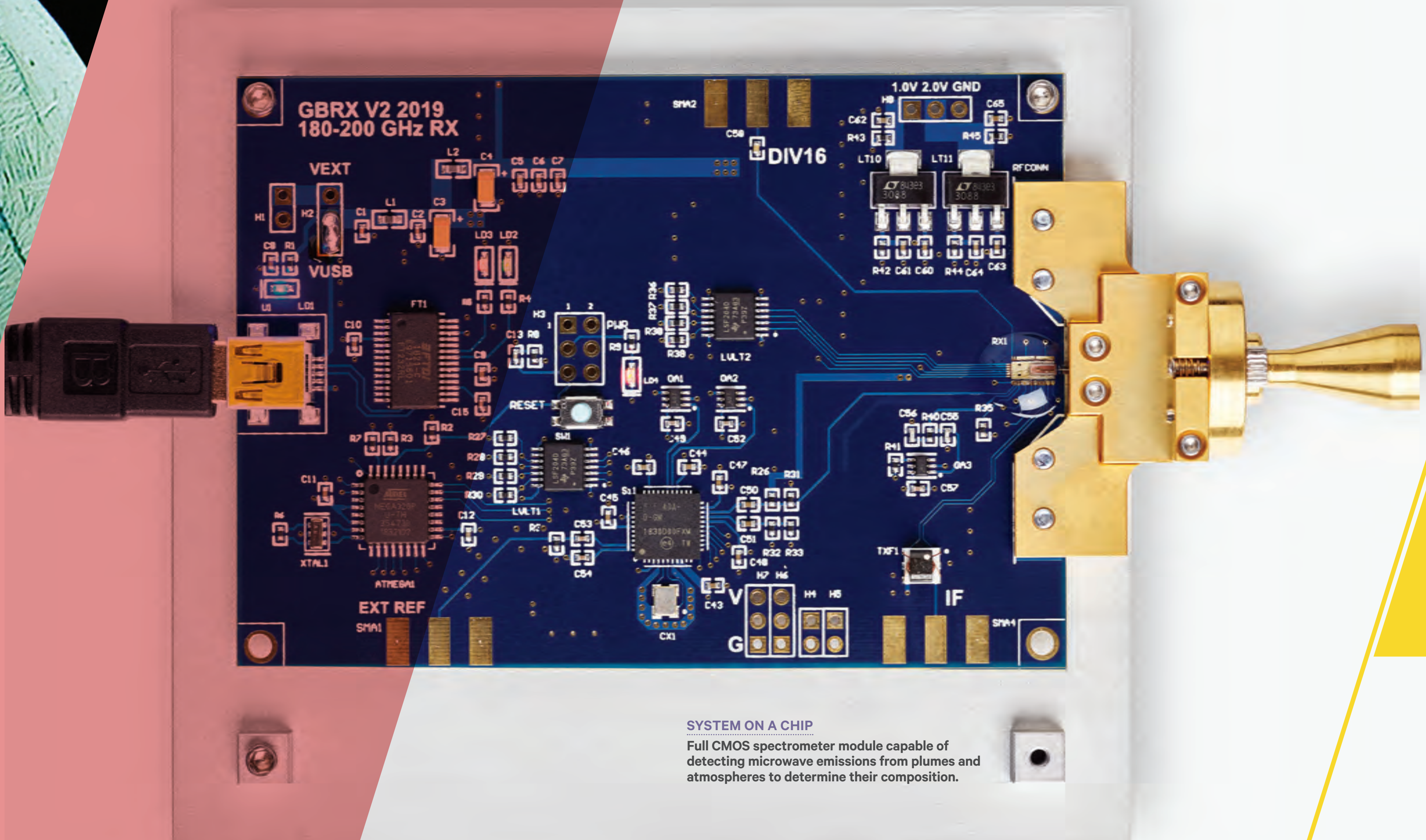
JPL pioneered advances in CMOS system-on-a-chip technology to miniaturize cameras for high-quality imaging on spacecraft. CMOS is present in all digital imaging, and makes cell phone radios, GPS, and cameras possible. The commercialization of the CMOS chip led to production lines that are now being leveraged to make even faster technology, at a fraction of the cost.

Furthermore, the new CMOS receiver chip is so small that it is surprisingly radiation hardened by design. The excited particles that comprise harmful radiation, and which cause damage to the cells of living creatures as well as harming electronics, are much less likely to hit the chip because of its small size. In the laboratory, it was measured to operate with a radiation dosage of 100 MegaRads (comparable to one hundred million chest X-rays), which is significantly superior to commercially available space hardware.

FOLLOW THE WATER
Saturn's moon Enceladus has gigantic water plumes erupting from its surface. These plumes are thought to originate in a vast sub-surface ocean concealed beneath its icy shell.

SWAP FOR SPEED

THE MINIATURIZED SPECTROMETER SET A WORLD RECORD FOR FASTEST COMPLEMENTARY METAL-OXIDE SEMICONDUCTOR (CMOS) RECEIVER CHIP



SYSTEM ON A CHIP

Full CMOS spectrometer module capable of detecting microwave emissions from plumes and atmospheres to determine their composition.

FLOCK TOGETHER

Swarms of spacecraft are expected to drive incredible changes in the way we operate everything, from daily deliveries to space exploration missions. As in the animal kingdom, a swarm provides more capability than any one of its elements. Humans are a prime example of swarm intelligence: a single person—no matter how smart—could never have achieved what even the earliest societies could do, technologically or otherwise.

JPL has led the way in the development of swarm technologies, from precision formation flying technologies to ongoing work on autonomous multi-robot teams. As this technology itself teaches us, however, we rely on experienced partners as well, and work with many different research and development partners across academia, industry, and government.

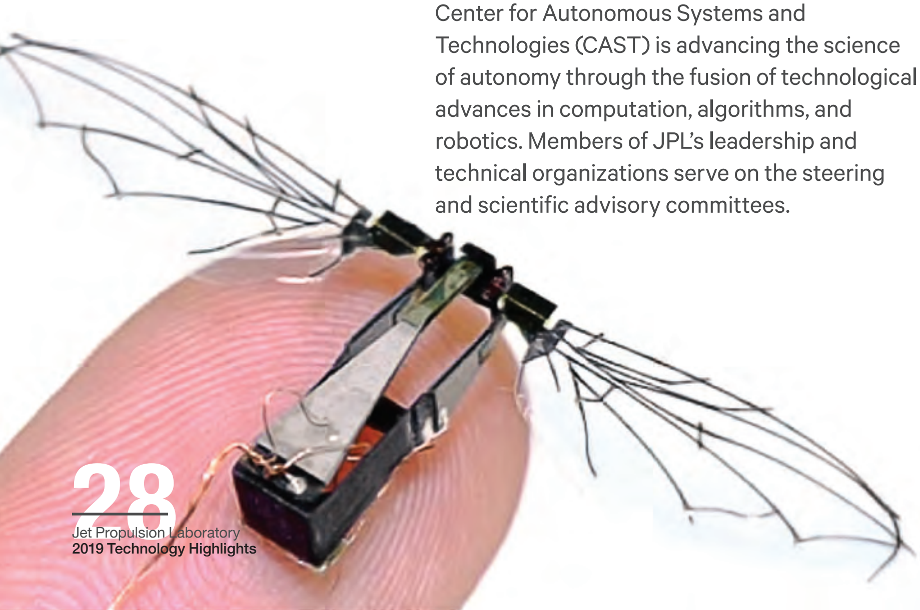
An embedded partnership with Caltech's Center for Autonomous Systems and Technologies (CAST) is advancing the science of autonomy through the fusion of technological advances in computation, algorithms, and robotics. Members of JPL's leadership and technical organizations serve on the steering and scientific advisory committees.

CAST complements JPL infrastructure with state-of-the-art instrumentation and vehicles for testing and validating new concepts in autonomy. It is equipped with a robotics assembly laboratory with advanced mobility capabilities and an aerospace robotics and control lab to simulate mobility for spacecraft operating alone or in formation. CAST also maintains an aerodrome facility that includes a large array of controllable electric fans that can generate realistic wind patterns for investigating aerial mobility in all weather conditions.

In 2018, JPL's swarm autonomy project developed a framework of distributed multi-spacecraft observation, demonstrated algorithms for relative precision navigation, and distributed estimation of a three-dimensional target's shape, combined with optimal planning and reconfiguration. Advances in sensing and perception, knowledge and model building, and motion planning account for the swarm autonomy elements advanced in 2018. New avenues of research include state estimation and monitoring, joint knowledge and understanding, behavior and intent prediction, as well as verification and validation.

Other space-related work includes the development and validation of autonomy algorithms and architecture for navigating to, approaching, and mapping small bodies such as asteroids, comets, and moons. These algorithms will also be useful for spacecraft flying in formation, which must remain aware of each other for safe and productive operation. Looking out to potential adaptations, this kind of technology could help coordinate automated traffic on roads and in airports, or automatic disaster response and mitigation.

SWARMS ARE FAR GREATER THAN THE SUM OF THEIR PARTS



SWARMS OF EXPLORERS

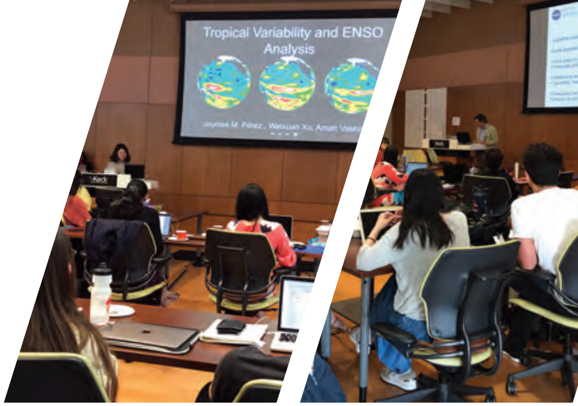
JPL is working with various partners on Micro-Air Vehicles, or MAVs, that can be used for exploration of celestial bodies with atmospheres.

DISTRIBUTED SYSTEMS BRING PLATFORMS TOGETHER TO ACHIEVE GOALS BEYOND THE CAPABILITY OF ONE INDIVIDUAL

GET IN FORMATION

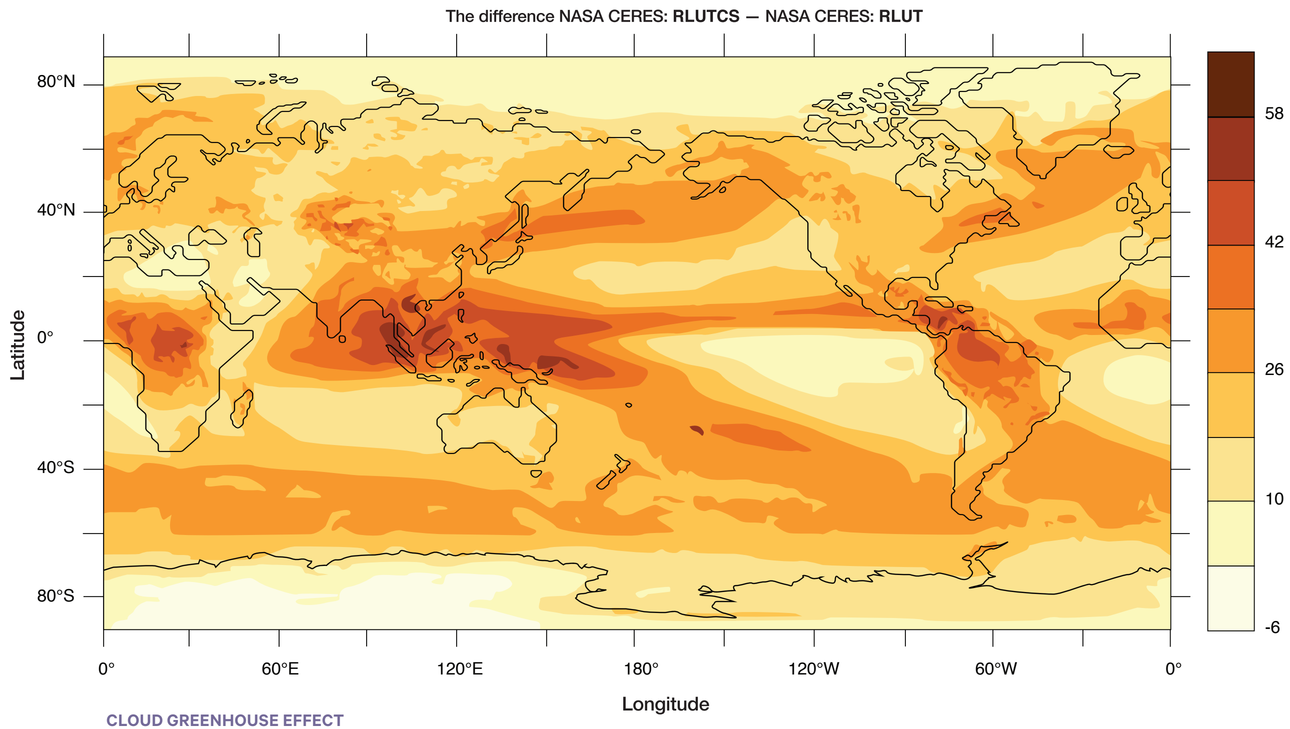
Professor Soon-Jo Chung's Space Robotics Lab within Caltech's Center for Autonomous Systems and Technologies (CAST) tests how spacecraft could coordinate with one another on orbit.

INNOVATIVE DESIGN HAS LED TO A CAPABILITY THAT ALLOWS COLLABORATION AT ALL SCALES OF ANALYSIS OF SCIENTIFIC DATA



SUMMER SCHOOL

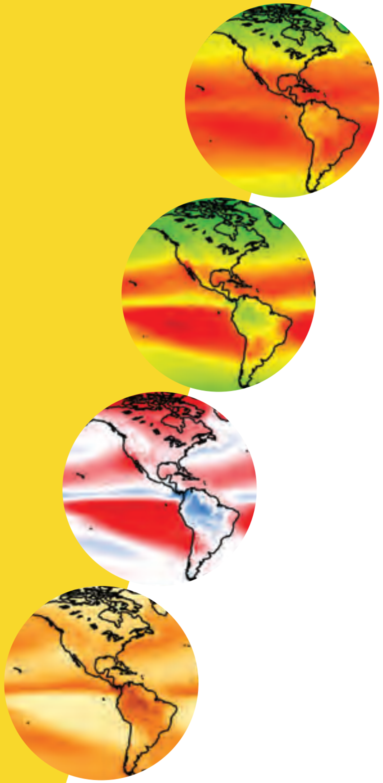
Groups of students learn to develop research projects with each other using CMDA. Collaborative science like this is needed more as information becomes too big and complex to handle by individual researchers.



CLOUD GREENHOUSE EFFECT

The large map shows how much clouds reduce the longwave radiation emitted to space across the globe. The figure was generated by CMDA using NASA data, and is one of many examples of the tool's visualization feature.

CLASSY CLIMATOLOGY



CLIMATE MODELS MUST BE VERIFIED INDEPENDENTLY FOR BIASES, AND VERIFICATIONS MUST BE REPEATED INDEPENDENTLY, THEN COMPARED COLLABORATIVELY FOR THE SAME REASON

The ability to manage data—not only to collect it, but to catalog, analyze, and communicate information—will be critical to future science missions. Today, data applications for teams and collaboration are a booming industry, but the specific needs of the science and technology community are simply not addressed. Specific needs include incorporating petabyte—millions of gigabytes—volumes of data that cannot be moved easily, include different data types from different sources, and require strict traceability of use to demonstrate the reproducibility of results. Incorporating different data also requires accounting for the inherent biases, or systematic errors, of raw climate data from the limited individual perspective, or spatial resolution, of each set of observational platforms. Scientists and students must be able to reliably show others how they learned something in order for it to become accepted as new knowledge.

The Climate Model Diagnostic Analyzer (CMDA) was conceived as a new way to diagnose model biases in contemporary climate models, identify the physical processes responsible for creating model biases, and incorporate that understanding into new models that reduce bias. The technology was developed as a collaborative research platform that integrates observational datasets and analysis tools to support the full life cycle of data analysis—from data discovery, customization, analysis and reanalysis, to publication and reproduction. Beyond data analysis capabilities, CMDA allows both scientists and students to share what they learn and how they came to their conclusions, including built-in interactive visualization. CMDA was designed like a web-based service to be scaled up for other users and applications, with no need to host its software on a user's device.

JPL developed the core capability of CMDA, which takes huge amounts of data about Earth's climate from over 92 sources, analyzes over 1500 datasets and capacity for many more. Expertise in understanding and processing satellite observation datasets, climate model outputs, and addressing key climate questions was enabling for this technology. Since then, the platform has been used to support group research project activities at JPL and to teach the next generation of researchers how to work collaboratively and effectively with as much data as any top-tier research institution.

The future of science missions lies not only in continuing to build the instruments and platforms that collect world-changing knowledge, but in developing the tools to place that knowledge in a broader context that also engages more people. Tools like CMDA that foster collaborative knowledge are critical to advancing our understanding of the universe and improving life on Earth.

OCCULT Cion

Radio occultation has proven to be unusually useful for spacecraft: from predicting weather on Earth and in space, to orbit determination. In the late 1990s, JPL transferred this technology to American industry, making weather forecasting much more accurate. Through partnerships with industry, JPL is now taking radio occultation technology to the next level by miniaturizing, digitizing, and making it much more affordable for users—opening the door to exciting new science and applications.

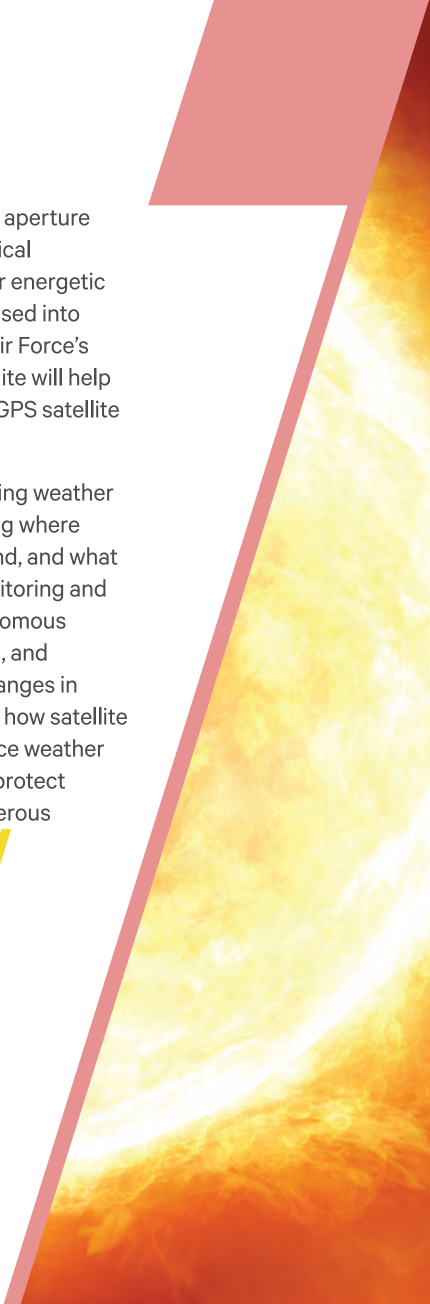
Receivers used to be too costly, power-hungry and heavy to fly on many missions, especially smaller satellites which have become very popular in low Earth orbits. Technologists designed a low-cost, low-power, low-mass navigation satellite (like GPS) signal receiver called Cion. Cion is a software-defined radio running under Linux, using C++, python scripts, and with modern toolsets allowing for straightforward reconfiguration of components, algorithms, and application software. After the initial design and delivery of navigation satellite signal firmware and software, it was licensed to GeoOptics by Caltech. Tyvak also partnered with this technology development and spinoff.

Cion is designed to orbit Earth on CubeSats and receive navigation satellite signals as they cut through Earth's atmosphere. Because there are so many navigation signal transmitters (approximately 48) and because the CubeSat-based Cion receivers are relatively inexpensive (about two million dollars each, including the satellite and the launch), dense temporal and spatial sampling of the atmosphere is now possible, providing complete global coverage in just a few hours.

Cion has also been selected for several NASA missions. Signals of Opportunity: P-band Investigation will investigate signals of opportunity in the P-band to measure the amount of water in snow by comparing the direct to the reflected measurement. While this has been verified on the ground, it will be the first use of this technique in space. The Sun Radio Interferometer Space Experiment (SunRISE) will consist of a constellation of CubeSats operating as a synthetic aperture radio telescope to address the critical heliophysics problems of how solar energetic particles are accelerated and released into interplanetary space. Finally, the Air Force's third Navigation Technology Satellite will help the Department of Defense make GPS satellite signals stronger and more reliable.

Cion's applications include improving weather forecasting (for example, predicting where and when a hurricane will reach land, and what areas will be flooded), climate monitoring and modeling, global navigation, autonomous operations for satellites near Earth, and space weather measurements (changes in radiation and magnetic field affect how satellite electronics work in orbit). The space weather data applications would also help protect the national power grid from dangerous electromagnetic events in space.

Cion USES SOFTWARE TO PERFORM RADIO OCCULTATION, A TECHNIQUE THAT MEASURES CHANGES IN A SIGNAL AS IT PASSES THROUGH AN ATMOSPHERE TO LEARN ITS KEY CHARACTERISTICS



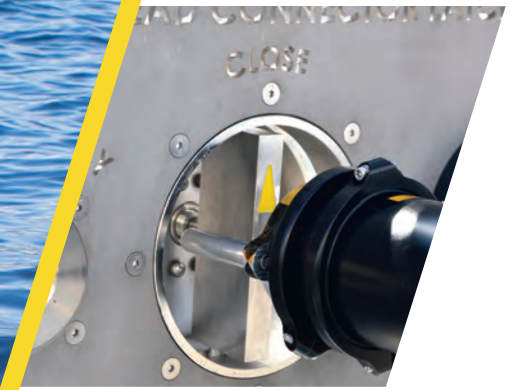
SunRISE

This swarm of satellites would use Cion to coordinate CubeSats in formation to operate as a synthetic aperture radio telescope to study solar energetic particles.

Cion RECEIVER

This cubesat instrument, designed by JPL and built by Tyvak for GeoOptics, is flying on the CICERO CubeSat constellation. Variations are planned for a variety of future NASA missions, like SunRISE.

LISTEN CLOSELY, BUT NOT WITH YOUR EARS



TESTING THE WATERS

Clockwise, AquaSimian: perception system and robotic arm; practicing a mock maintenance routine using its 7 DOF all electric arm; being deployed for a field test validating its capabilities underwater.

AQUASIMIAN IS AN UNDERWATER MOBILE MANIPULATION AND PERCEPTION SYSTEM

MONKEY MEETS WRENCH

EXPLORING THE OCEANS THAT COVER ICE-ENCRUSTED MOONS LIKE EUROPA WILL REQUIRE AUTONOMY ON DEXTEROUS ROBOTIC PLATFORMS

The quest to discover life beyond Earth has led us to the planetary oceans under moons encased in ice. Places like Jupiter's moon, Europa, and Saturn's moon, Enceladus, may harbor extraterrestrial life in the oceans beneath their kilometers-thick frozen crust. Missions to explore regions of the solar system so far from Earth will need to operate autonomously. Existing technology development has focused on being able to see and move in the air versus underwater, where light moves differently and seeing anything accurately is a challenge in and of itself, let alone being able to see and interact with things, which is necessary for a mission to an ocean world.

JPL's Underwater Mobile Manipulation team developed the AquaSimian Robotic Limb & Underwater Perception System, a technology suite that works like hands and eyes underwater. The suite consists of a seven degree-of-freedom (DOF), all-electric arm and 3 DOF wrist. The wrist uses three independently articulated jaw mechanisms with an integrated force-torque sensor for handling objects, and stereo camera perception system to see clearly in murky underwater environments. The perception system enables 3D scene reconstructions within a 2m underwater workspace. Automated targeting software calculates the position and orientation of known objects within the scene, allowing a human operator to select objects. The software then automatically computes the optimal path to complete the task and previews it for the operator to decide whether or not to execute.

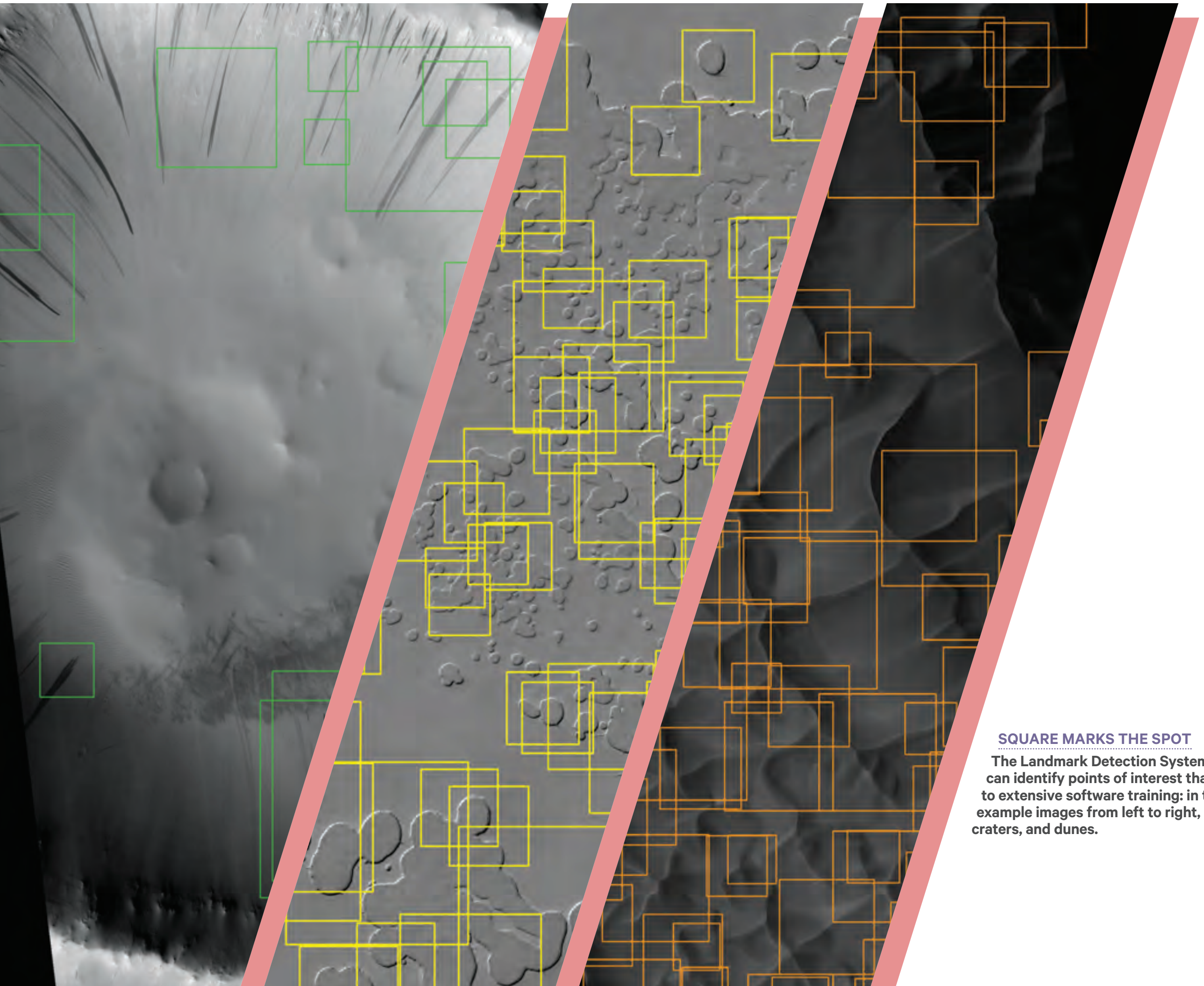
Some of this technology was originally developed for the JPL RoboSimian to compete in the DARPA 2015 Robotics Challenge. Adapting this for underwater use, technologists had to develop all-new, sealed actuators and force-torque sensors for the arm and wrist. Additionally, the perception system had to be redesigned to account for distortion in the underwater environment, and a projection system was added to enhance edge detection and deliver high-resolution, real-time reconstructions. These reconstructions were developed using a new pattern projection approach, which can capture a large field of view in one shot, as opposed to laser line scanning approaches used on land.

On Earth, AquaSimian technology could be used to maintain the Internet's worldwide network of cables, most of them underwater. These cables can run as deep at 7km below the ocean and servicing them is difficult. Divers can dive to a maximum of 200m beyond which only expensive remotely operated submersibles go. Autonomous systems like AquaSimian would greatly improve serviceability and reduce operational costs of critical underwater infrastructure.

LOOKING FOR SIGNS

NASA missions and their science data have put the entire solar system in everyone's pocket. The Planetary Data System (PDS) contains a huge number of images from all over the solar system, captured by NASA and other countries' instruments and missions. The PDS holds over 2 petabytes of data, and at last count, was growing at an average of 12.1 terabytes every day (one petabyte is a thousand terabytes, which is a million gigabytes). For comparison, a top-of-the-line personal computer may come with 1–4 terabytes of storage. This challenge of managing massive amounts of information is referred to as a "data deluge." The sheer number of images is more than any person or team of people can manage.

The ability to search complex data, including images, for content of interest is critical to the future of science. Future missions will bring even more data—going from static images to video will be a tectonic shift in data management. The PDS is only one of many such repositories, not even close to being the largest science database.



SQUARE MARKS THE SPOT
The Landmark Detection System can identify points of interest thanks to extensive software training: in the example images from left to right, slopes, craters, and dunes.

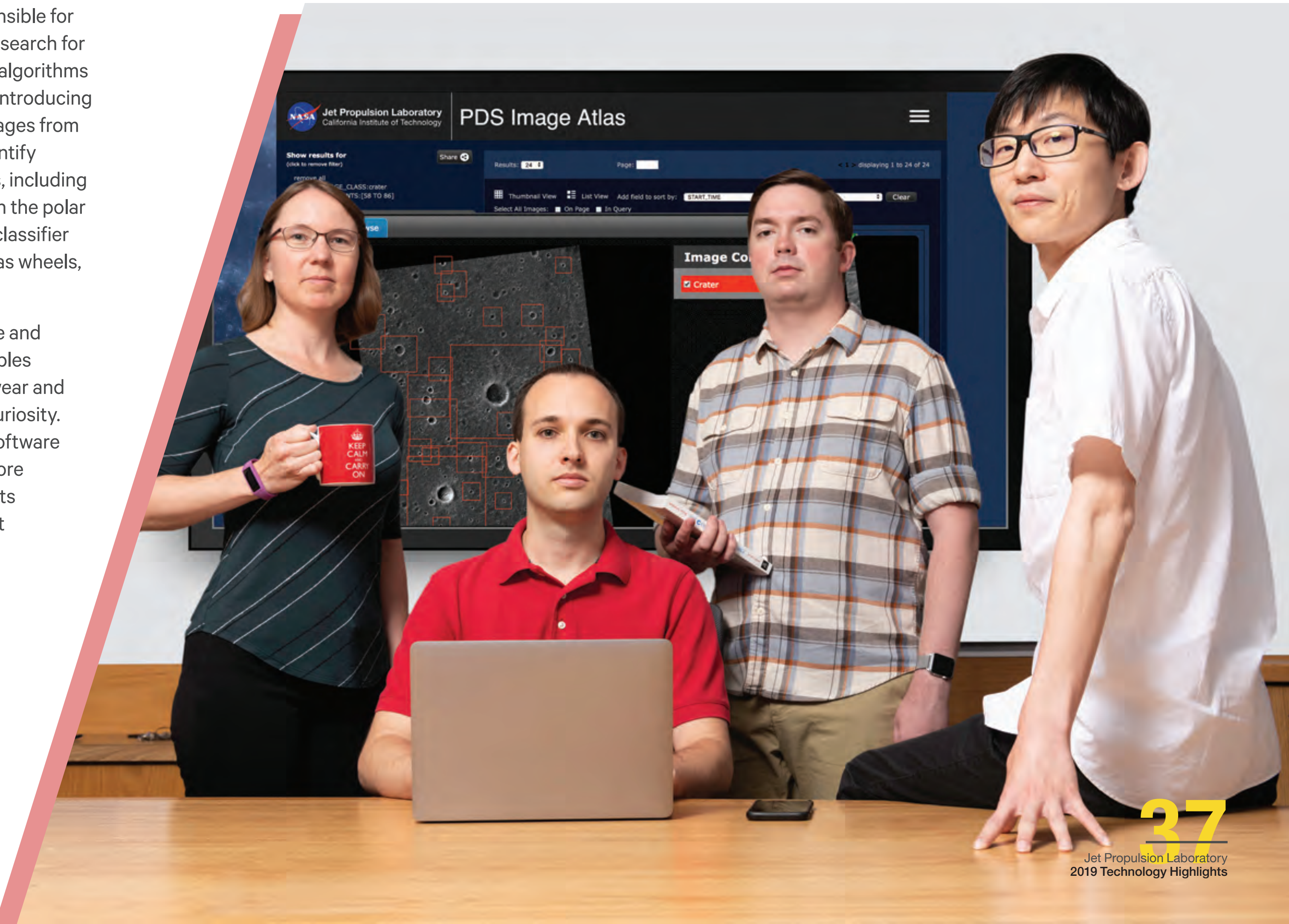
SEARCHING THE SOLAR SYSTEM JUST GOT A LOT SMARTER

On top of that, about every three years, our total data storage doubles—expanding in ways traditional techniques cannot match. The data demands of future science missions mean that any serious analysis will require significant computer assistance.

JPL, in cooperation with Caltech, has been using transfer learning to teach a program to identify and classify images of Mars. Inspired by how we search for images online, the team created an intuitive tool with the high reliability and detail needed for scientific research. The team responsible for creating the first content-based image search for planetary science initially trained their algorithms on much larger Earth data sets before introducing the software to a smaller number of images from Mars. They trained one classifier to identify "landmarks" within Mars orbital images, including craters, dunes, and seasonal changes in the polar regions of Mars. They trained another classifier to label rover images by content, such as wheels, instruments, and surface features.

This effort is already producing science and engineering return. For example, it enables mission planners to visually track the wear and tear on the wheels of the Mars rover, Curiosity. Currently, the team is preparing their software for use with other instruments' data, more content types, and across more datasets —potentially bringing more science out of every mission.

THE MORE WE EXPLORE, THE MORE WE SEE—AND THE MORE WE SEE, THE MORE WE NEED TO SORT WHAT WE ARE LOOKING AT TO UNDERSTAND IT. MACHINE LEARNING HOLDS THE KEY TO LEVERAGING MORE INFORMATION THAN THE HUMAN BRAIN CAN HANDLE



PEOPLE BEHIND THE SOFTWARE

Principal Investigator Kiri Wagstaff and her team, from left Gary Doran, Kevin Grimes, and Steven Lu, pose with the image content classification system they developed.

SCIENCE PLATFORMS MUST TRAVEL THROUGH EXTREME ENVIRONMENTS WHILE MAINTAINING DIFFERENT TEMPERATURES FOR ONBOARD INSTRUMENTS

SMART MATERIALS & STRUCTURES TO SURVIVE

Left, harsh extraterrestrial environments will test current thermal systems. Middle, revolutionary thermal management systems have been created through the pairing of “feature rich” heat transfer devices with additive manufacturing technology. Right, the additively manufactured material demonstrates its ability to wick water extremely efficiently.

COOL IT

Space systems must weather extreme heat and cold, while their sensitive instruments must be kept at specific, often different temperatures to work. Today, several different systems are used to distribute and manage heat. This adds power, mass, and size to systems with strict constraints. As we see more small platforms, and more ambitious missions, with more sophisticated instruments take flight, thermal management can decide if a mission is feasible or not. Additionally, access to extreme environments, like Venus's sweltering surface or Europa's frozen crust, demand innovative solutions to the problem of managing temperature.

To address this challenge, active and passive thermal technologies are now being incorporated into multi-functional structures. This advance was enabled by additive manufacturing of seamless metallic forms of varying density, ranging from solid to porous. An example of such an advanced thermal system uses evaporation for cooling within a component's structure. Fluid passages are built-in with porous media, or holes, for passive liquid-to-vapor phase control. This allows for the transfer of heat through these holes and passages, while keeping the structure's spatially uniform temperature. It works the same way large trees are incredibly strong yet able to move water from the ground to top branches.

The new technology does this by taking advantage of the isothermal process of boiling a fluid. For example, boiling water stays at 100°C even when the stove adds more heat. Keeping temperature constant through boiling is a thousand times more efficient than using a solid and a hundred times more efficient than just using a liquid for transferring heat. This efficiency means significantly reduced power needs. Tests have shown this approach is more than ten times less power hungry than what is flown today. This new thermal system also has less than half the mass of current temperature control systems, and the mass savings increase with heat load. This technology can be adapted to nearly any form, and 3D printing of multi-functional complex structures in one build makes production faster, cheaper, and more adaptable while making the product more robust.

Similar integrated thermal designs could benefit almost anything that needs temperature control, including off world habitats, power generators, batteries, electronic devices, and more. This advance also allows for recycling waste-heat by managing temperature in phases which let excess heat be used when needed. This not only changes how space science missions can be designed, it also suggests potential applications in sustainability and sustainable design all over the world.

PATTERNS OF HOLES AND FLOW CHANNELS TO CONTROL TEMPERATURE ARE ONE EXAMPLE OF "SMART" MATERIALS

ADDITIVE MANUFACTURED THERMAL CONTROL

Shown are 3D printed heat sinks that incorporate variable porosity internal structures for liquid/vapor phase control, providing orders of magnitude improved thermal performance.

BEAUTIFULLY BOGUS

Wide field astronomical surveys image and produce hundreds of thousands of source detections per night. Manually sorting through these to see whether observations are real astronomical sources or bogus artifacts of telescope optics and image processing would always leave astronomers playing catch up with their data. Knowing the telescope is looking at something astronomers actually want to observe will significantly improve how much astronomy gets done each night.

The Zwicky Transient Facility (ZTF) at Palomar Observatory watches the night sky to see how the universe is changing, from stars exploding to black holes colliding in faraway galaxies. It uses a new, 47-square-degree field-of-view camera, which can scan more than 3750 square degrees each hour. Repeated imaging of the northern sky, including the galactic plane, will produce a catalog of how light from different sources changes. With nearly 300 observations every year, it is ideal for studies of variable stars, binaries, active galactic nuclei, and asteroids. ZTF uses image subtraction, where an old picture of the night sky is subtracted from a new image of the same frame to discover changing astronomical events, like supernovae, or pulsars. Image subtraction produces a large number of candidates, many of which are bogus false positives, so automated verification is required to filter out the bogus from the real.

JPL expertise in machine learning and data science led to involvement with Palomar and ZTF. To solve the image subtraction problem, technologists developed a software suite called Real-Bogus. Real-Bogus features new machine learning algorithms and data pipelines that ingest data from crowdsourced inputs, from platforms like Zooniverse, and generate Real-Bogus scores optimized for each survey. It needs to handle conflicting annotations on training data, discover any data contamination, and respond to shifts in data characteristics. Indeed, data contamination has been the biggest challenge to other Real-Bogus efforts. As a result, JPL has invested in automated discovery of data contamination and robust evaluation systems for finding sub-pockets that may be causing a disproportionate amount of error.

Real-Bogus was deployed at ZTF at the start of science operations in early 2018, and has regularly delivered updates as science operations yield more astronomical "reals" and data pipeline upgrades results in new classes of "boguses." A new image classifier will also be deployed onto the data pipeline hosted by MIT Lincoln Laboratory for the U.S. Air Force's Space Surveillance Telescope (SST) in 2019.

IN AN EVER CHANGING UNIVERSE, WE MUST OFTEN ASK OURSELVES: IS THIS REAL, OR BOGUS?

SURVEYING THE UNIVERSE

The Palomar Observatory's 48-inch Samuel Oschin Telescope looks out at the night sky, imaging hundreds of potential astronomical events with ZTF, and identifying which ones are true astronomical observations with Real-Bogus.

MACHINE LEARNING AND DATA SCIENCE FOR ASTRONOMY IS FINDING COSMIC EVENTS THAT WERE ONCE DIFFICULT TO VERIFY

COASTAL OCEAN SCIENCE IS KEY TO ONGOING EFFORTS TO PROTECT OUR BEACHES, PORTS, & EVERYTHING ELSE ALONG OUR COAST

ASSEMBLY INSPECTION
JPL Engineers, Dr. Shannon Statham and Dr. Sharmila Padmanabhan, inspect the HRMR flight unit after it is assembled to the AMR-C instrument structure for Jason-CS/Sentinel-6.

WATCHING THE WATER
The Jason-CS/Sentinel-6 mission will carry the next generation of science instruments, including HRMR, for high-precision sea-level measurements. These measurements are increasingly important as coastlines become more active.

LITTORAL TECH

The world's oceans and coastlines are changing, and knowing how and where will help us plan–or react–as needed. The Jason-CS/Sentinel–6 mission is attempting to address this need. A joint partnership of NASA, the National Oceanic and Atmospheric Administration, the European Organisation for the Exploitation of Meteorological Satellites, and the European Space Agency, with the French Centre National d'Études Spatiales providing technical support, as part of a two-satellite mission. The Jason-CS satellite will carry a radar altimeter package to continue the high-precision altitude measurements of prior missions, Jason-2 and -3. It will complement the high-inclination measurements on Sentinel-3 to obtain high-precision global sea-surface topography for the marine and climate user community. By measuring global sea surface height to an accuracy of < 4 cm every 10 days, this mission is helping us determine ocean circulation, climate change, and sea level rise. However, these missions have had difficulty in assessing coastlines because of the inability to account for the presence of land in these measurements.

HIGH RESOLUTION MICROWAVE RADIOMETERS WILL ENABLE SCIENTISTS TO ACCURATELY STUDY HOW OCEANS INTERACT WITH COASTS, WHICH WAS PREVIOUSLY VERY DIFFICULT TO DO GLOBALLY

JPL is contributing an experimental new technology for this mission to be able to study global coastlines. The High-Resolution Microwave Radiometer (HRMR), combined with the Supplemental Calibration System, form the Advanced Microwave Radiometer–Climate Quality instrument, or AMR-C. The aperture can be significantly reduced, improving size, weight, and power trade-offs in spacecraft design. HRMR's high-frequency channels (90, 130, and 168 GHz) demonstrate the capability of a high-frequency radiometer to extend measurements into coastal zones. Legacy missions used lower-power frequencies (18.7, 23.8, 34 GHz) that were not able to provide accurate measurements along coastlines. HRMR will not only validate the ability to extend these measurements, but will be able to provide them more accurately than ever before. HRMR is expected to achieve over twice the accuracy of previous technology, which is measured as 0.7 cm path delay correction. The updated calibrator also allows for calibration on-orbit by using a secondary movable and mountable reflector. Prior to this, slewing, or moving the entire spacecraft sideways and then back between measurements was necessary to maintain accuracy.

Combined, these technical advances mean that we will now be able to accurately measure changes in ocean height along coastlines. The importance of coastal areas cannot be overstated, with over 80% of people living within 62 miles of coastline, and 40% within 37 miles.

HRMR FLIGHT UNIT

A close up of the HRMR flight unit shows the compactness of this new technology. At 2.5 kg total mass, this small addition to AMR-C will validate significant improvements to radiometer and Earth Science missions.

MY SPIDEY SENSE IS TINGLING

THROUGH ANYTHING CLEARLY

External MQS base-station systems for navigation inside buildings or houses for first-responder applications. This technology can sense clearly through any material at any thickness within its current range.

NEW APPLICATIONS OF FUNDAMENTAL PHYSICS OFTEN OPEN THE DOOR TO RADICALLY NEW CAPABILITIES

GPS and cellular service often suffer indoors or underground. When flying a spacecraft through an asteroid, this inconvenience can become catastrophic. Similarly, a first responder to a disaster situation knowing exactly where they and others are can mean the difference between life and death. Electromagnetic (EM) waves, like the kind that carry our voices over communication channels or location over GPS, are weakened by many kinds of material, especially thick minerals and metals, such as in the walls of buildings or underground.

JPL is pioneering research and development of a totally new paradigm for sensors: magnetoquasistatic (MQS) fields. Existing techniques, from sonar to GPS to cell towers, fail to provide reliable connections or accurate data in environments that deny line of sight. This is because of the nature of EM waves, which weaken as they pass through solid matter.

TAMPERING WITH PHYSICS
Principal Investigator Darmindra Arumugam is seen here making on the fly adjustments to electrical components during a field test of MQS technology.

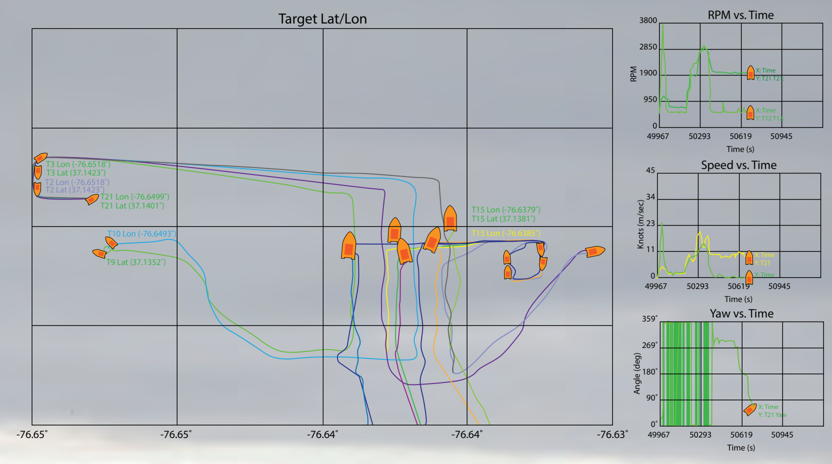
'MAGNETIC VISION' CAN SEE THROUGH SOLID MATTER VERY ACCURATELY, ALLOWING SPACE MISSIONS TO NAVIGATE REMOTE, HAZARDOUS ENVIRONMENTS LIKE INSIDE ASTEROIDS OR PLANETARY ICE SHEETS—AND HELP FIRST-RESPONDERS ON EARTH NAVIGATE DISASTERS

However, at low enough frequencies, the magnetic part of EM becomes dominant for circular or coil exciters and detectors, making it interact with the world differently. MQS fields, unlike EM fields, are not degraded by most of the barriers that stop the signals we rely on in our daily life, space missions, and disaster situations. Currently, we do not have any other way of seeing through solid objects without involving bulky machinery and harmful radiation—and even then, with poor accuracy. MQS, by contrast, has tested location accuracy down to the centimeter, and does so reliably in a number of test conditions, including through walls, underground, and underwater.

The Department of Homeland Security identified MQS for its life-saving potential. The Precision Outdoor and Indoor Navigation for Emergency Responders, or POINTER, project is working to miniaturize this technology to cell phone size. The technology is also being combined with traditional radio frequency techniques and artificial intelligence to deliver higher accuracy and reliability. Currently, the technology is limited by range to about 100 meters from another device, so technologists are working on collaborative navigation techniques to extend this range over much greater distances. MQS was first tested in one dimension, then in 2D, then in 3D to shrink it to a size that a first responder could carry comfortably, at an affordable cost. Currently, the team is iterating its field tests to further refine—and potentially commercialize—the hand-held version of this technology.

MQS has the potential to carry data, too, the way we use EM fields to carry cell phone and GPS data today. This could also allow spacecraft deep inside another planet to recognize where it is, where it should go, and to communicate its discoveries with Earth, seamlessly.

HUMAN-ROBOTIC TEAMS ENABLED BY ARTIFICIAL INTELLIGENCE WILL BE ABLE TO EXPLORE BEYOND THE CAPABILITY OF ANY INDIVIDUAL



SITUATIONAL AWARENESS

This graphic is a close recreation of the read-out commanding autonomous boats to work together under human direction. This graphic eliminated a lot of the labeling meant for technical operation.

THE FUTURE IS FLEETING

Live capture of JPL human-robotic fleet team moving in an autonomously coordinated formation by human command.

FLEET-ING GLORY

As a bold new frontier in robotics and swarms open up, it is important to make sure humans and these new systems work well together. This area of technology development is also known as human-robotic teaming. Swarms can also be designed to work in conjunction with humans, which will be a complete change in how most of us work—imagine having several robotic assistants help complete any complicated task based on what a person tells them to do. This is of interest to NASA and JPL, in particular, for use in distributed space systems, astronaut work and life, off-world construction, and more.

The Coast Guard and the Navy are also interested in being able to operate multiple autonomous boats with one human supervisor for rescue missions and patrols. The Navy recently held a two-week test event of competing technology to do just that. The JPL team's software resulted in formations converging 20% more quickly than the next best competitor, ran on smaller-footprint hardware, and had lower integration overhead. Further, it was the only technology to pass all of the stress tests, where vehicles had to run in close proximity, at high speeds, and on collision courses, over and over. This demonstrated the technology's capability to autonomously maintain safe maneuvers and plan routes to do what the human operator tells them to.

The Control Architecture for Robotic Agent Command and Sensing (CARACaS) is a JPL-developed hybrid control architecture that has provided the foundational software for various robotic platforms' autonomous operations. Ocean-surface vehicle applications include cooperative patrol, vehicle escort, and mine clearing. Automated obstacle-aware path planning and trajectory optimization allow vehicles to self-adapt to dangerous sea conditions, and higher-level autonomous functions decide which vehicle should do what task and when. This technology also incorporates resource-aware coordination and task allocation under uncertainty, all of which is essential to being able to operate autonomously as a team.

One of the more amazing things about these technologies is how many different ways they can be reconfigured for breakthroughs in areas we used to think needed separating. The advances made in this initiative are already being transferred to land and air platforms. Further, CARACaS has already been adapted for underwater use, to explore off world oceans under ice shelves.

SAFETY CRITICAL SOFTWARE IS A CORE COMPETENCY AT JPL, AND SAFETY CRITICAL CONTROL OF MULTIPLE VEHICLES OPERATING IN CLOSE PROXIMITY WITH HUMANS WILL BE INTEGRAL TO FUTURE MISSIONS

RACE TO THE FUTURE

JPL AI COMPETES WITH WORLD CLASS HUMAN DRONE RACER

RIGHT TURN RIGHT TIME

Visual features are selected from the view of onboard cameras, and tracked at high rate. The result is a versatile mobility platform that can navigate 3D terrain at high speed.

INTELLIGENT MACHINE-BASED MAPPING AND PLANNING ALLOWS ANY VEHICLE TO COMPETE AND OUTPERFORM ANY HUMAN OPERATOR

TORQing IT

TORQ AI-driven racing drone, optimized for speed and onboard compute, packs a serious punch. Onboard planning algorithms determine the optimal path for the drone to take.

Artificial intelligence (AI) is changing the way we work, live, and play. In particular, the current boom in AI is coming from mechanizing basic skills we humans may take for granted, like being able to see and know what we are looking at, or being able to tell why any two things are different. Fundamentals like this have far-reaching impacts in many sectors from manufacturing to transportation, from disaster response to construction—and, of course, space exploration and science.

JPL and Google developed an AI, data, and visualization system as part of a project called Tango. It successfully demonstrated 3D visualization and mapping as well as centimeter-level position accuracy from smartphone technology. That included constructing detailed textured models of indoor spaces in real-time and on memory-constrained systems. Significant effort was spent implementing fault-detection and addressing underlying software engineering challenges. Possible future work includes interpreting 3D maps that it builds, like being able to identify what different things are, and using the technology suite for other robotic tasks on Earth and in space.

The technology was placed on an aerial drone as part of a project called Tango on Racing Quadrotors, then held a race with a world-class drone pilot. The race was in a warehouse that was set up with obstacles to challenge even a top-tier pilot. The AI-driven drone was comparable in speed to the expert human pilot, but outperformed in several other key metrics. The AI was extremely accurate in completing its race–much more so than the experienced aerial drone pilot—and its performance does not drop over after a day of work, the way a human's performance does.

The work has proven, as expected, to have applications in many areas. Using this core technology, JPL has pushed the limit of how fast a mobile platform can go–in this case an aerial drone–while also mapping its path independently. This kind of work enables autonomous exploration platforms across domains, and could one day help a helicopter on Mars explore on its own, and make discoveries that change our understanding of the universe, even as we rest.

ULTRA-COLD QUANTUM GAS COULD BECOME A NEW INGREDIENT IN FUTURE TECHNOLOGIES

The Cold Atom Laboratory (CAL) flying 254 miles above us on the International Space Station uses advanced technology to enable researchers to study ultracold atoms and Bose-Einstein Condensates (BECs) remotely from Earth–which will enable previously impossible technology.

At high temperatures, atoms behave as particles, but at very cold temperatures their wave nature becomes more pronounced. Using lasers and magnetic fields, a vapor cloud can be directly cooled to form a very pure and very cold atomic gas. At critical temperature and density, the wavelengths of the atoms begin to overlap and they share the same macroscopic wave function. The very cold, very dense cloud of atoms then becomes a fifth state of matter, (solid, liquid, gas, plasma, and) BECs. In CAL, these atoms can reach temperatures below 100 picokelvin, or -460 F.

Studying BECs from space holds unique benefits. This state of matter is extremely sensitive to gravity, so large drop towers are built to study them on Earth. In space however, the microgravity environment allows them to be observed much longer.

CAL has three atomic species, and allows 24 different quantum states to be prepared (with an infinite number of mixtures and superpositions), and the precise control of interactions between atoms in certain states. CAL can also perform atom interferometry and probe a variety of this new state of matter's properties. High- and low-resolution imaging allow scientists to view atom clouds from two directions. New cooling techniques, decompression and delta-kick cooling, provide access to an unexplored range of temperature and enables precise focusing, cooling, and shaping of atomic clouds. CAL also pioneered an entirely new technique: chip-based sympathetic cooling of potassium via rubidium.

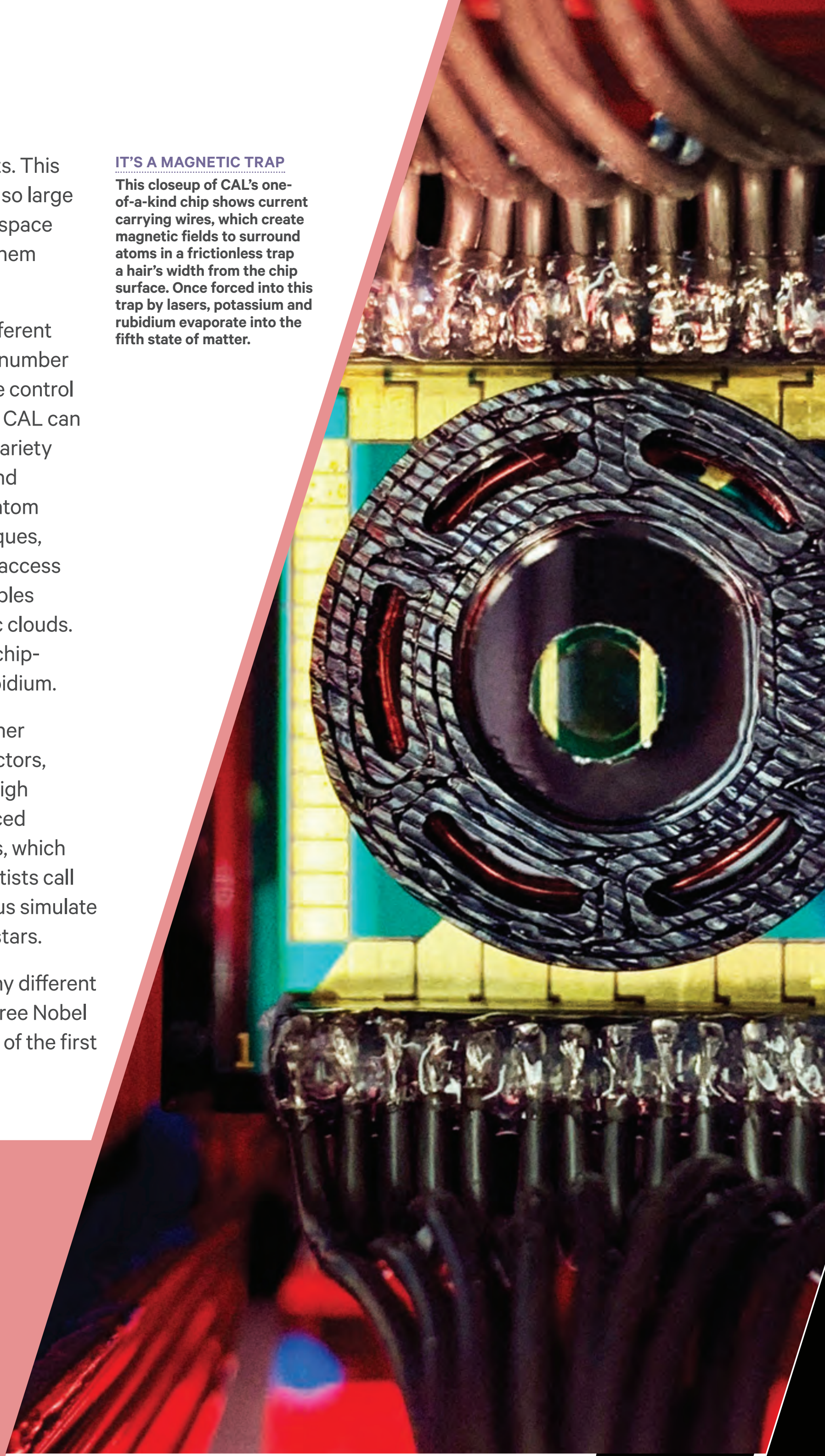
Cold atom research can contribute to making finer accelerometers, high-temperature superconductors, quantum key distribution for encryption, ultra-high precision atomic clocks, and much more advanced sensors—particularly for gravity measurements, which are key to unravelling the mystery of what scientists call "dark matter" and "dark energy." BECs even let us simulate inaccessible places, like the interior of neutron stars.

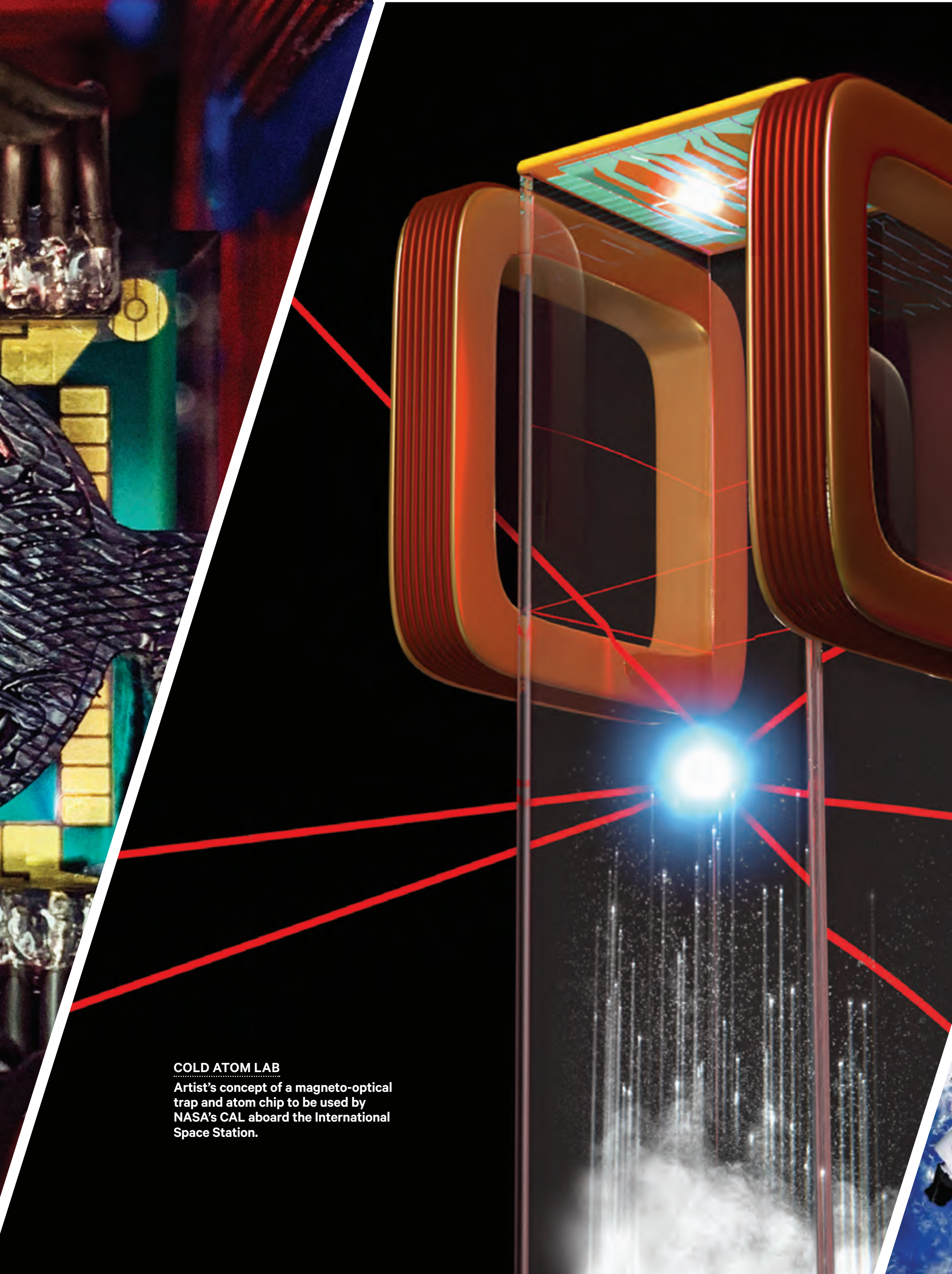
CAL is designed to host the experiments of many different researchers from around the world, including three Nobel Laureates in cold-atom physics. CAL is also one of the first labs to be entirely remote controlled.

The Cold Atom Laboratory launched to the ISS on May 21, 2018.

IT'S A MAGNETIC TRAP

This closeup of CAL's one-of-a-kind chip shows current carrying wires, which create magnetic fields to surround atoms in a frictionless trap a hair's width from the chip surface. Once forced into this trap by lasers, potassium and rubidium evaporate into the fifth state of matter.





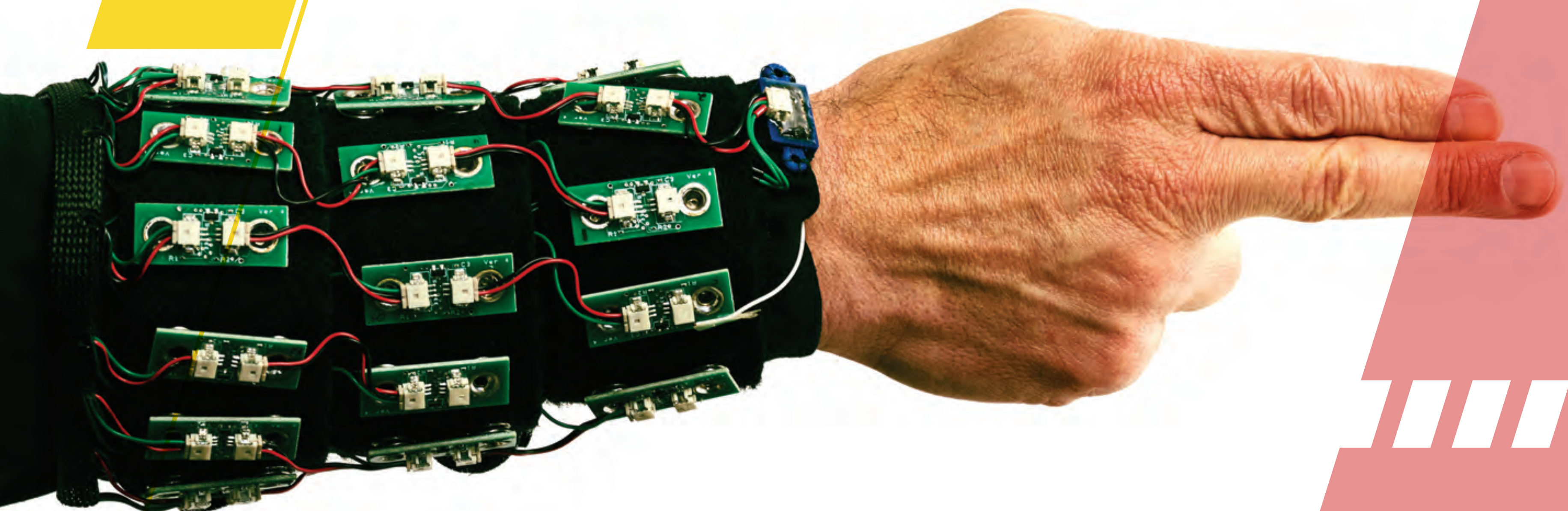
COLD ATOM LAB
Artist's concept of a magneto-optical trap and atom chip to be used by NASA's CAL aboard the International Space Station.

UNKNOWN BECKONS

ADVANCES IN LASERS AND NOVEL COOLING TECHNIQUES HAVE ALLOWED US TO CREATE THE COLDEST ARTIFICIAL ENVIRONMENT EVER —MINIATURIZED TO FIT IN A MINIFRIDGE

NEW STATE OF MATTER
NASA's CAL, now on the US Lab Destiny Module of ISS, is creating the fifth state of matter, Bose Einstein Condensates, and studying these ultracold quantum gases on orbit.

HELPING HANDS



BIOSLEEVE LETS USERS CONTROL MACHINES REMOTELY WITH GESTURES

WALK THIS WAY

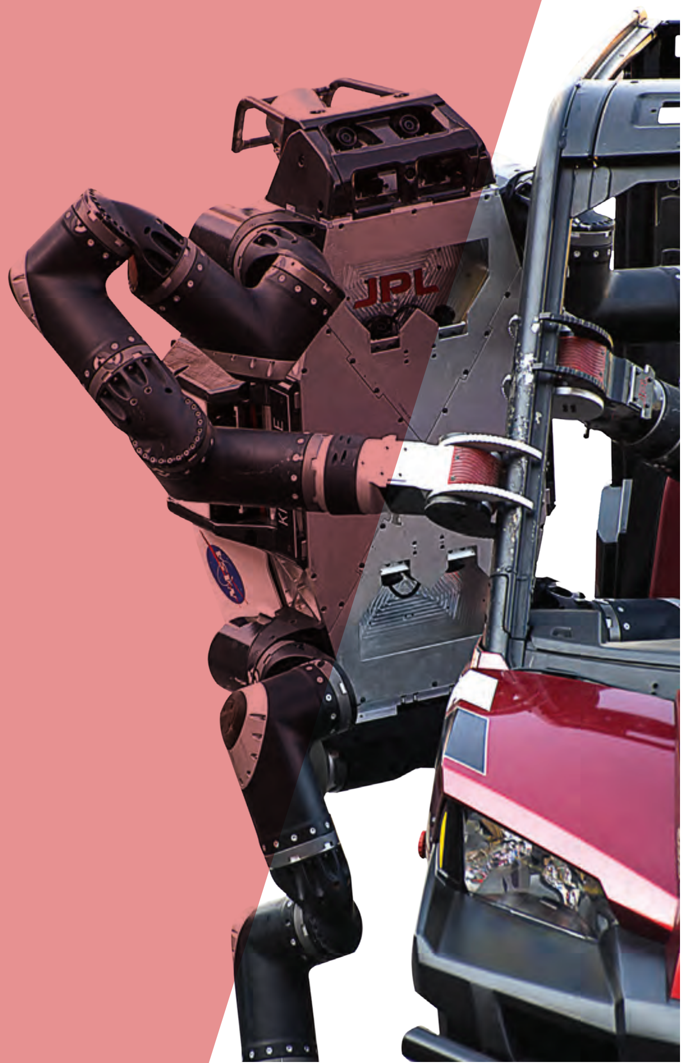
BioSleeve uses wearable sensors to detect minute changes in arm muscles based on which gesture a hand is making. These signals are then translated, letting people use gestures to command all kinds of machines–in this case, RoboSimian being commanded to enter a vehicle. This technology could let people naturally coordinate several robots in sequence with their hands.

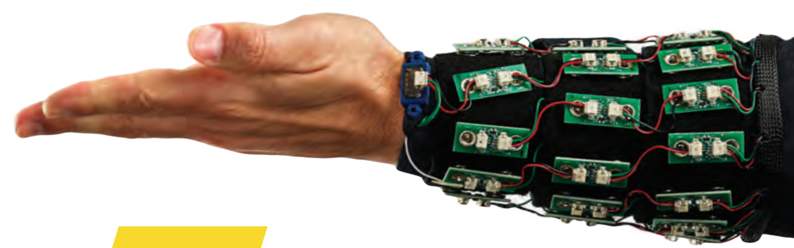
We depend on machines more and more in our daily lives; being able to communicate effectively with them is already critical for both efficiency and safety. The JPL BioSleeve is a gesture-control interface for Human-Robot Interactions or Human-Computer Interactions. Potential applications include astronauts working with machines in orbit or on another world; exoskeleton control; virtual and augmented reality; prosthetics; muscle and arm monitoring for therapy and medicine; security; and disaster response to name a few.

BioSleeve is based on the innovative idea that a dense array of sensors could be built into clothing to monitor and recognize muscle and arm activity. Worn on the arm, it leaves hands free. The sleeve contains a dense array of 24–32 bipolar electromyography (EMG) sensors, several inertial measurement unit (IMU) sensors, and a processing board that performs in-sleeve data collection, feature extraction, pattern recognition, and command mapping. Two machine learning algorithms, support vector machine and random forests, have been applied for the gesture classification.

BioSleeve requires no fine positioning of sensors, as most current prosthetic interfaces do, because the software used for initial calibration can learn and store the sensor patterns. First a person trains on a set of up to 20 static hand/wrist gestures, while BioSleeve collects 6–10 seconds of data for each gesture. After training, the BioSleeve has performed at above 95% correct gesture classification, and can hold above 90% for at least 4 hours. The IMUs also enable recognition of larger dynamic motions of the whole arm, including natural gestures such as waving and pointing directions. The BioSleeve team has successfully demonstrated control of a wide variety of telerobotic platforms, both in simulation and real-world field tests, including small wheeled rovers, the JPL Robosimian robot, a QinetiQ Dragon Runner (20 lb. robot used for bomb disposal), an experimental prosthetic hand, and even a commercial BB-8 robot. BioSleeve has also been used to control simulated platforms, including models of Canadarm2 and SPHERES on the International Space Station.

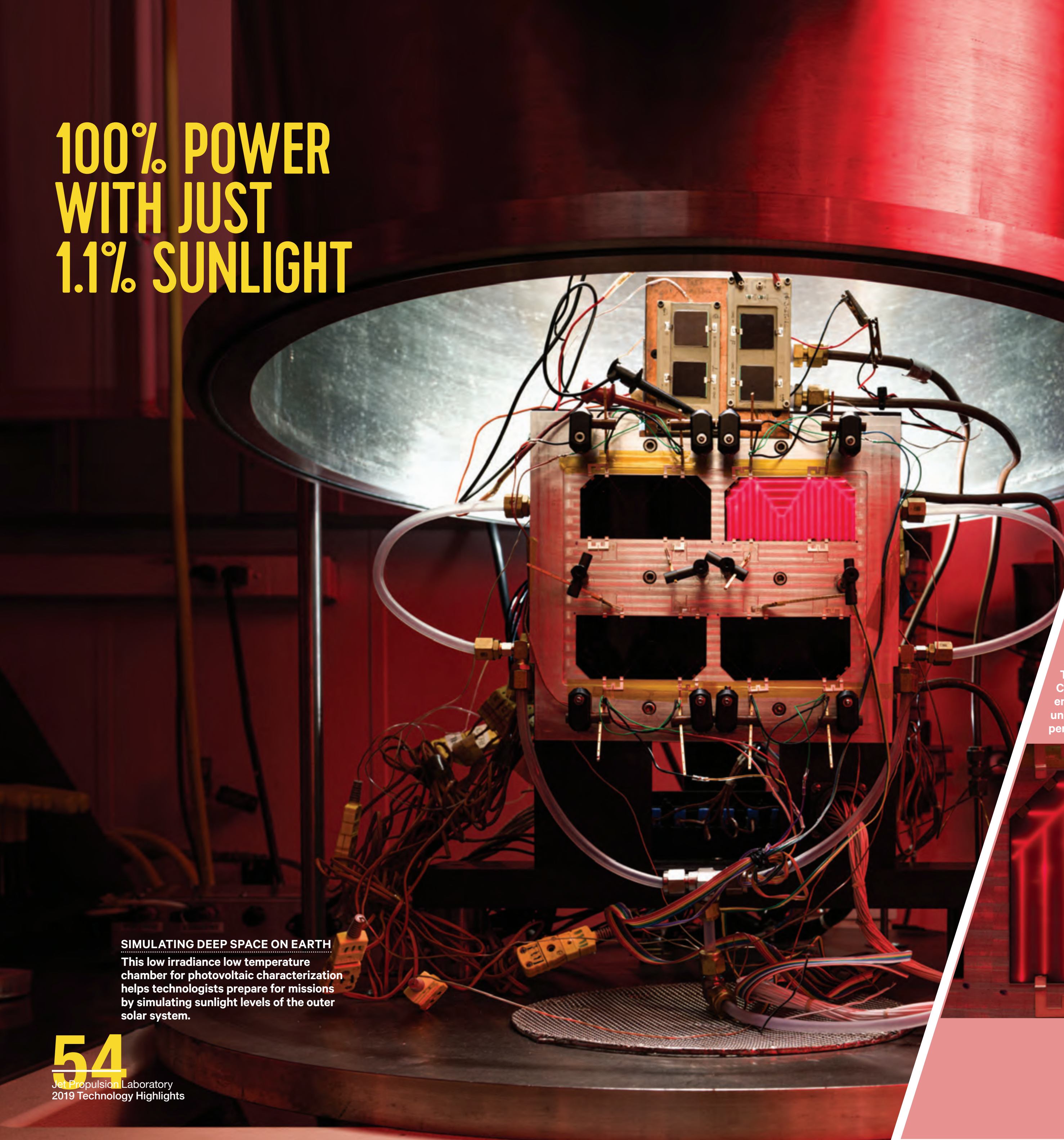
The BioSleeve team was able to prove this technology works in a relevant space environment. The team continues its work on BioSleeve in the Human-Robot Interfaces Lab. The combination of EMG with IMUs for gesture control is novel, contributing to award of a U.S. Patent for this technology.





COMMUNICATING WITH MACHINES WILL BE CRITICAL IN A FUTURE WHERE HUMANS AND INTELLIGENT ROBOTS ARE PARTNERS

100% POWER WITH JUST 1.1% SUNLIGHT



SIMULATING DEEP SPACE ON EARTH

This low irradiance low temperature chamber for photovoltaic characterization helps technologists prepare for missions by simulating sunlight levels of the outer solar system.

CELL BY CELL

These images show, the Saturn-Optimized Solar Cell, from left to right: during recent tests in an environment simulating sunlight near Saturn; its unique design, Principal Investigator Andreea Boca performing tests on her technology.

STAYING SUNNY

Electricity powers everything we do, and our space missions are no different. While spacecraft have access to more than one type of power source, solar arrays have become the mainstay of most mission architectures. One major issue with solar power in deep space is that a lot less sunlight is available when flying far from the Sun. 1 astronomical unit (AU) is the distance between the Earth and Sun. So for example, the light intensity in the Saturn system, at 9.5 AU, is only 1.1% of what it is at 1 AU. Saturn solar arrays would need to be about 90 times larger than Earth-orbit solar arrays generating the same amount of power. This is why solar arrays have yet to be used to power spacecraft beyond the orbit of Jupiter (at 5.5 AU).

To make solar arrays viable as far as the Saturn orbit and beyond, their size and mass have to be reduced significantly. One of the best ways to accomplish that is by increasing solar cell efficiency. However, low light intensity and the low operating temperatures that go with it, can be extremely challenging to cell efficiency. Commercial off-the-shelf space solar cells that were originally developed for Earth-orbit applications will typically perform poorly under deep space conditions—which is why we need solar cells specifically developed for deep space.

This next-generation solar cell is optimized for operation in the Saturn system. The cell technology has demonstrated an average laboratory-measured efficiency of 37.3% at beginning of life and 35.5% at end of life under Saturn conditions. Under Jupiter conditions, the demonstrated efficiency is even higher: 39.4% at beginning of life. In addition, this cell is 30% lighter weight at the assembly level than standard solar cells. The high efficiency and low mass make this cell ideally suited for solar arrays on deep-space missions up to 10 AU. For comparison, the Juno spacecraft currently holds the record for farthest solar-powered spacecraft from the Sun. Its solar array is made of three wings. If the next-generation deep-space solar cell had been available to Juno, just two wings would have been sufficient to power it.

In 2018, the team completed iterative design, fabrication, and testing; demonstrated performance at beginning-of-life and end-of-life while meeting all performance objectives; and successfully concluded the solar cell development effort, infusing the resulting technology into a solar array development task. Follow-on work includes integrating the cells into a Saturn-optimized solar array, and even potentially extending the solar cell operation capability out to the Uranus orbit (at 19.2 AU).

NEW SOLAR CELLS WILL ALLOW SPACECRAFT LARGE AND SMALL TO BE POWERED BY THE SUN MUCH FARTHER AWAY THAN BEFORE, AND WITH LESS NEED FOR FUELS

CARPE ALL DIEM

THE WORLD'S FIRST CLIMBING ROBOTS, DEMONSTRATING TECHNOLOGIES THAT COULD GRIP THEIR WAY TO PLACES WE HAVE NEVER BEEN

Millions of people know and love JPL-built NASA Mars rovers, that have made so many incredible discoveries on Mars. However, one major drawback to these wheeled robots is their reliance on flat, safe, two-dimensional terrain. Not only does this approach require extensive planning to avoid rocks or uneven terrain, it also prevents access to critical science locations. As on Earth, cliffs and caves on other worlds host some of the most readily available geological records. On Earth at least, those usually include fossils, and caves can provide refuge to microorganisms. To break out of flat surface exploration and access extreme terrain—where some of the most intriguing science targets may be found—technologists developed the world's first climbing robots.

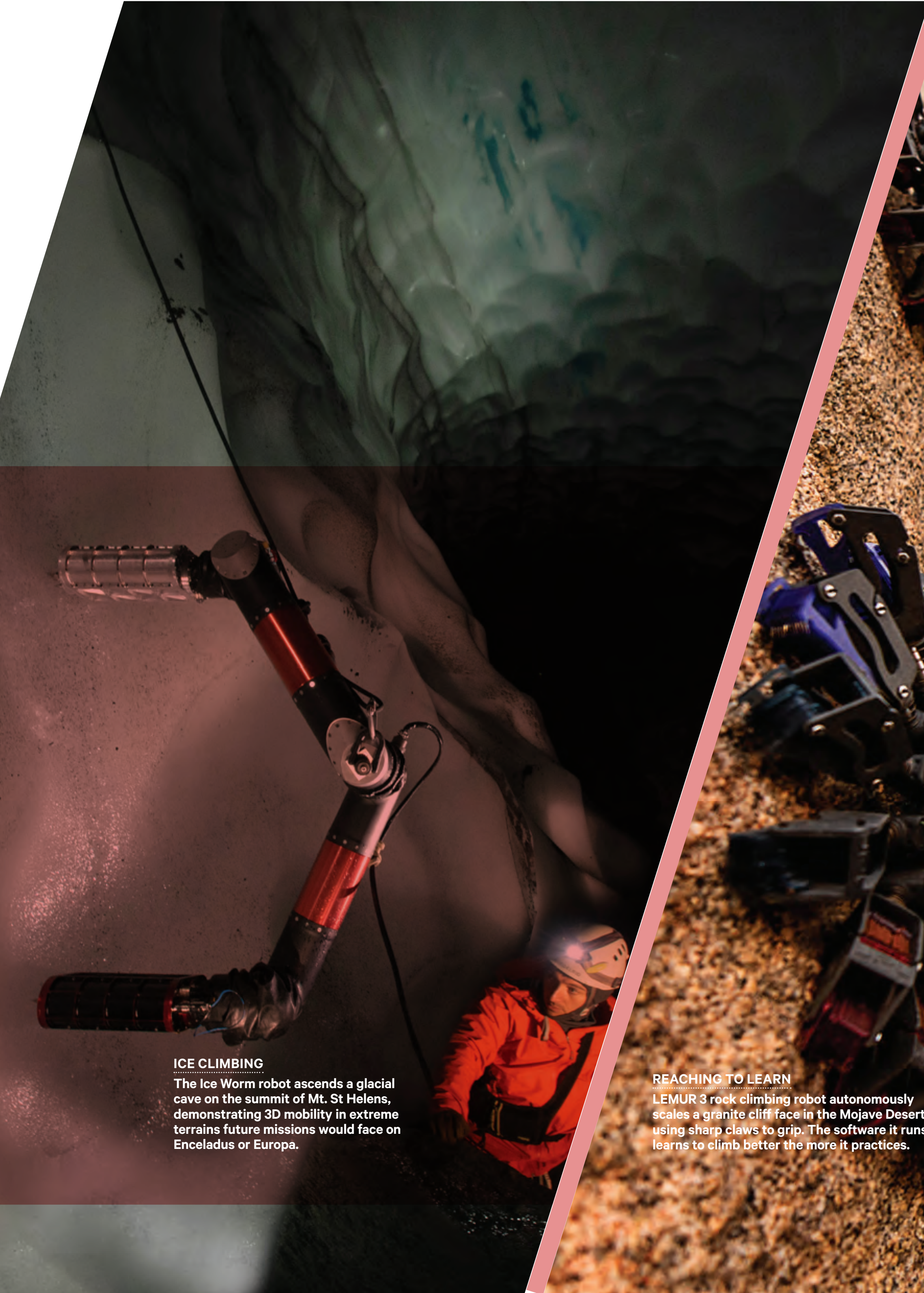
The Limbed Excursion Mechanical Utility Robot (LEMUR) employs many novel technologies in a single, autonomous machine. The robot's microspine grippers, made up of hundreds of tiny hooks, allow it to grip any kind of rocky surface, a technology originally inspired by the way geckos' feet can grasp any surface. In addition, LEMUR's onboard lidar uses light to detect the shape of the rock the robot is climbing, similar to the way a bat uses sound to detect rock shapes. Not only that, as LEMUR climbs, its intelligent software learns to climb better.

LEMUR's ability to learn and perform autonomously is necessary because a human cannot see and plan for the robot's climb in the level of detail required, particularly when the climb is going to take place on another planet. LEMUR can also carry many different scientific instruments, including those for compositional analysis, life detection, and sample acquisition, to learn about other planets in the solar system.

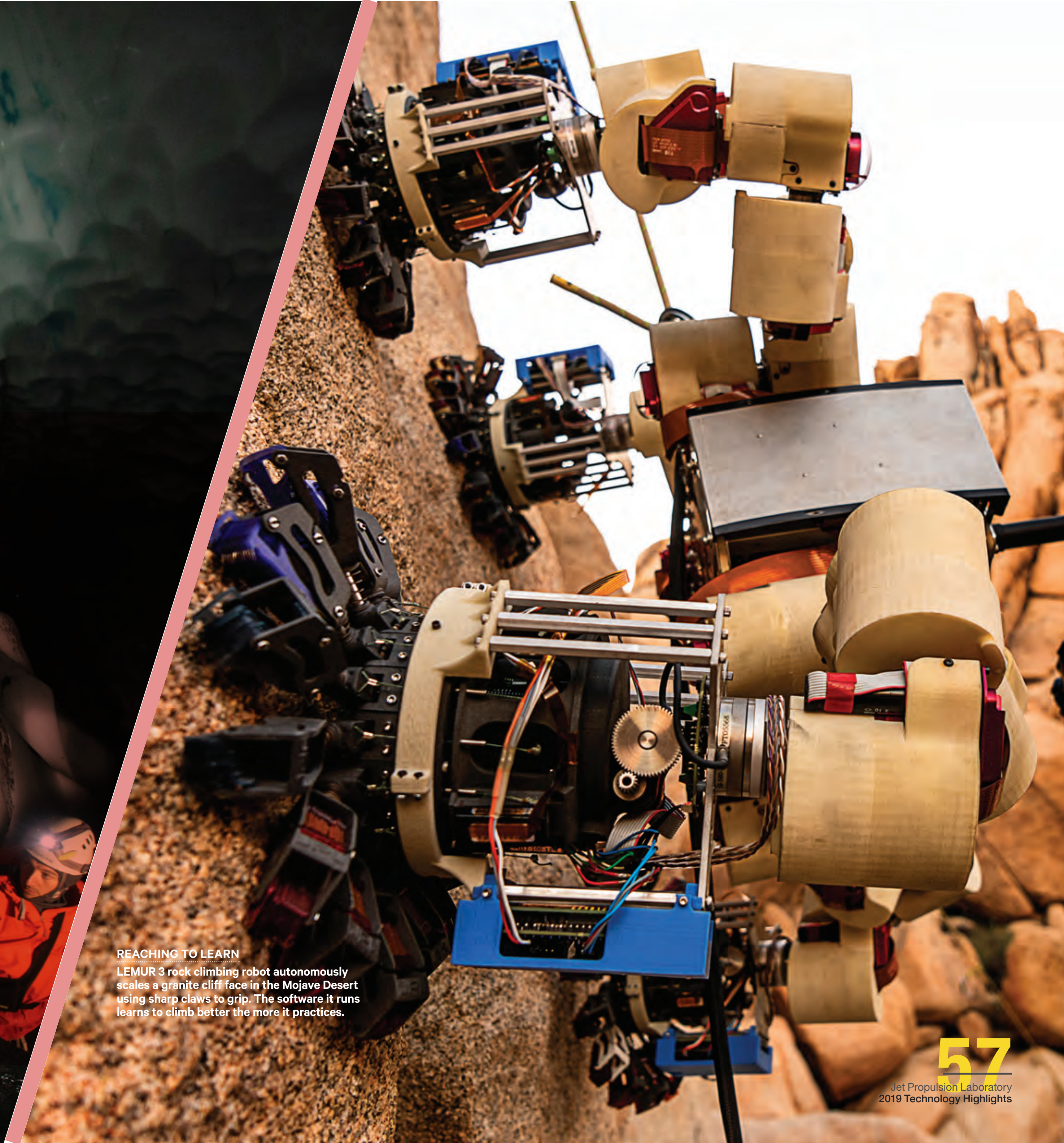
An offshoot of this design is IceWorm, the world's first ice-climbing robot. IceWorm uses a specially designed pick, sturdier and more powerful than what human ice-climbers would employ, to grip and climb up, down, or side-to-side on ice. JPL teams successfully tested LEMUR's ability to climb on the cliffs of Death Valley, and IceWorm in the ice caverns of Mount St. Helens in Washington State.

With extreme terrain robots, people can one day access active vents on Enceladus, the cliff faces of Mars, caves on the Moon, and even comets. Elements of this technology can also have great value on Earth, from robotic factories, to search-and-rescue missions, helping to detect or deliver supplies to people trapped in caves, mines, or other difficult-to-reach places.

COMBINING ROBOTIC, SENSING, AND MACHINE LEARNING TECHNOLOGIES IS BRINGING THE MOST DIFFICULT TO REACH YET TANTALIZING PLACES IN THE SOLAR SYSTEM WITHIN OUR GRASP

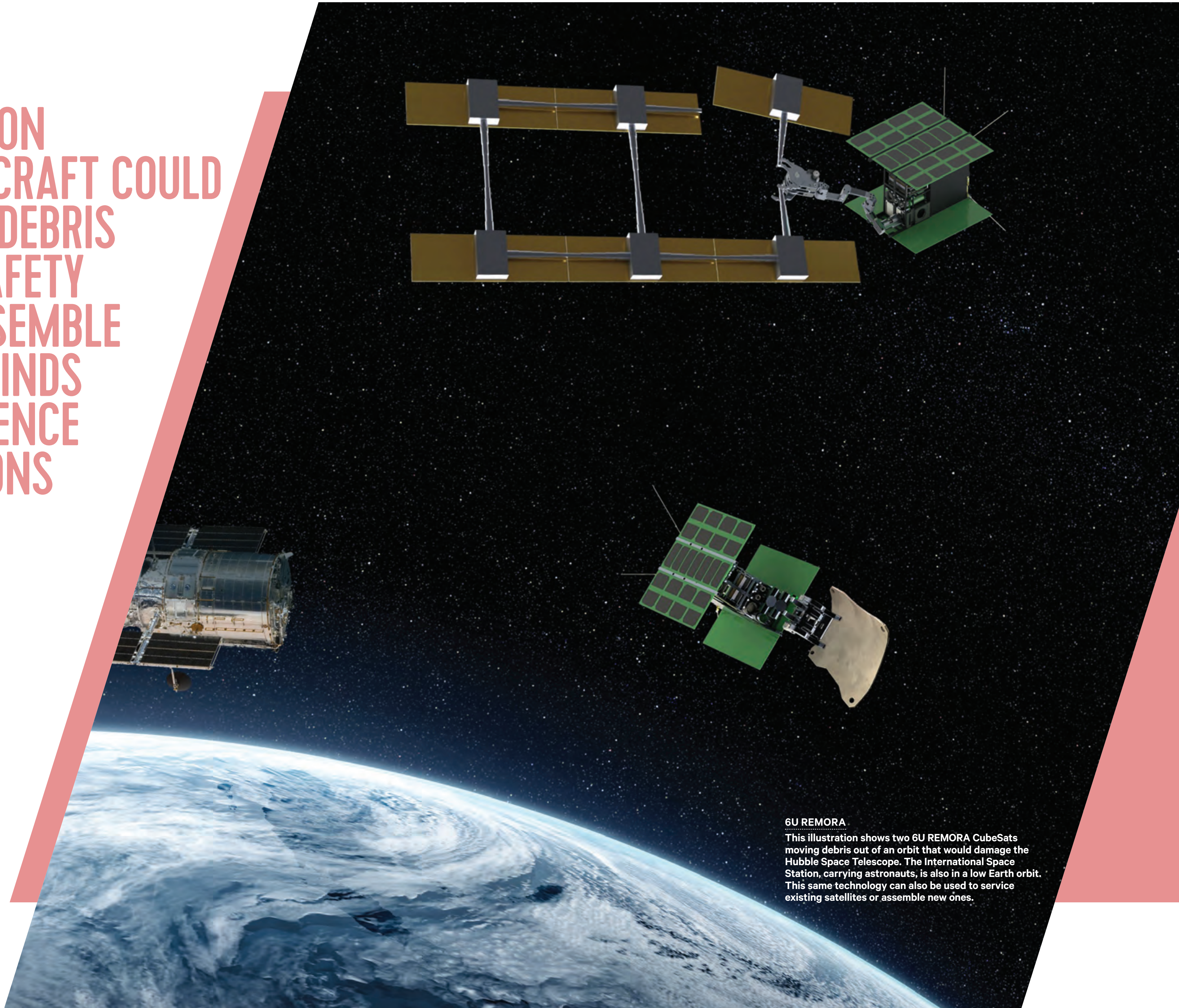


ICE CLIMBING
The Ice Worm robot ascends a glacial cave on the summit of Mt. St Helens, demonstrating 3D mobility in extreme terrains future missions would face on Enceladus or Europa.



REACHING TO LEARN
LEMUR 3 rock climbing robot autonomously scales a granite cliff face in the Mojave Desert using sharp claws to grip. The software it runs learns to climb better the more it practices.

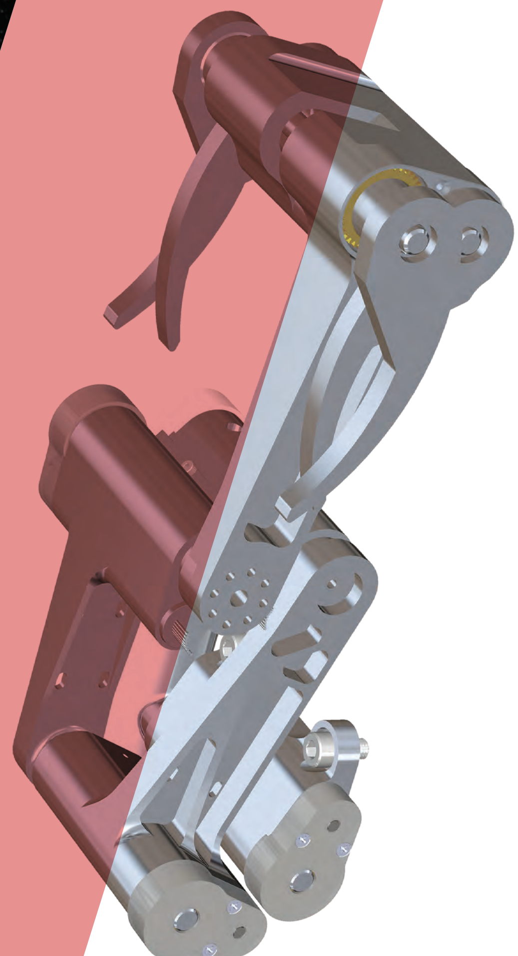
ARMS ON SPACECRAFT COULD MOVE DEBRIS FOR SAFETY OR ASSEMBLE NEW KINDS OF SCIENCE MISSIONS



6U REMORA

This illustration shows two 6U REMORA CubeSats moving debris out of an orbit that would damage the Hubble Space Telescope. The International Space Station, carrying astronauts, is also in a low Earth orbit. This same technology can also be used to service existing satellites or assemble new ones.

HIGH FIVE



ROBOTIC ARM

This computer model of the REMORA miniature robotic arm for a CubeSat shows it in its extended configuration, with a reach of 300mm. The snaking design allows the arm to coil up into a space just 0.5U, while being effective at gripping many kinds of features.

As vast as space is, there are only so many orbital slots for spacecraft that want to operate in the most sought-after real estate above us: low Earth orbit (LEO). Mega-constellations of hundreds of spacecraft being deployed now, and more planned, make LEO increasingly risky to operate in. Debris from past human activity in Earth's orbit is increasing, but what if we could steer some of that debris before a collision occurs? That is what the technologists behind the REMORA mini robotic arm proposed in response to a Defense Advanced Research Projects Agency (DARPA) call for solutions to mitigate the debris problem before it impacts our growing use of space here on Earth.

The REMORA team developed the concept for a 6U or 12U CubeSat (1U is 10 cm^3) to rendezvous, berth, track, and, if needed, prevent collisions with large space debris objects. Their design solution was a robotic payload with a computing element, cameras, miniature robotic arm, and end-effector (the "hand"). The REMORA CubeSat could rendezvous with a piece of debris and use the robotic manipulator to anchor itself to the target object. Once anchored, the CubeSat could track the debris and, if needed, alter the debris object's trajectory to prevent a collision.

REMORA was originally conceived as an end-to-end concept of a debris rendezvous mission through design of a 6U and 12U CubeSat. The team performed extensive simulations of rendezvous and berthing, designed, built, and tested the five degrees of freedom miniature robotic arm for a CubeSat. It only takes up about 0.5U volume, and is 300 mm long when extended. Two end-effectors were designed: one (0.5U volume) for grasping space debris, and another much smaller one for forming clusters of these CubeSats in a form of in-space robotic assembly. In a laboratory setting, the team demonstrated that the payload elements can be used to grasp various features that are commonly found on large space debris objects, including pipes, rocket nozzles, and payload adapter rings.

REMORA was originally designed for debris mitigation, but has also been adapted for in-space servicing and assembly. REMORA equipped satellites could perform maintenance and assemble parts remotely and robotically on orbit. The REMORA CubeSat and its robotic payload could also be used for new Earth Science or Astrophysics missions, forming clusters of science payloads through assembly, or even by linking different CubeSats. This capability would change fundamental assumptions about how missions are designed, launched, and operated, enabling new science missions.

REMORA MINIATURIZES ROBOTICS TO CREATE A NEW CAPABILITY FOR EVEN THE SMALLEST OF SPACECRAFT: RENDEZVOUS, PROXIMITY OPERATIONS, COLLISION AVOIDANCE, AND IN-SPACE ASSEMBLY

A PINCH OF ATOMS

The miniaturization of instruments relies on nanoscale and atomic scale production techniques. At these scales, even the tiniest imperfections can ruin an instrument or component. Techniques to address this challenge are also generating interest in many different industries for use in industrial processes, including scaling down microelectronics even further.

Atomic layer deposition (ALD) is widely used to deposit thin films of materials for many industrial applications. The process involves pulsing two or more gaseous elements on a surface of interest in a reactor. These are pulsed in sequence, but never at the same time.

The interaction is "self-limiting:" once the thinnest possible layer is achieved and all the interaction points of each molecule are filled, the bonding stops. By varying the number of these pulses, it is possible to grow materials uniformly and with high precision on arbitrarily complex and large material surfaces. Atomic layer etching (ALE) on the other hand is a much newer process that is still maturing as a technology. It can be considered the inverse of ALD, where a single molecular layer is removed in any desired shape or thickness, rather than added. ALE can be complementary to ALD by removing unwanted layers and adding in desired ones respectively.

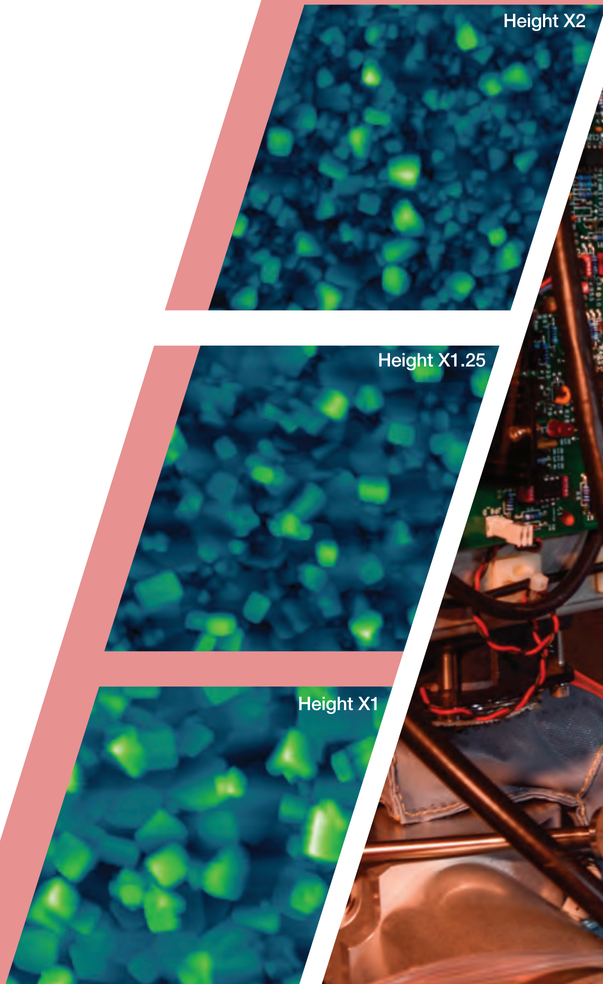
BUILDING BETTER SYSTEMS FROM THE ATOMS UP

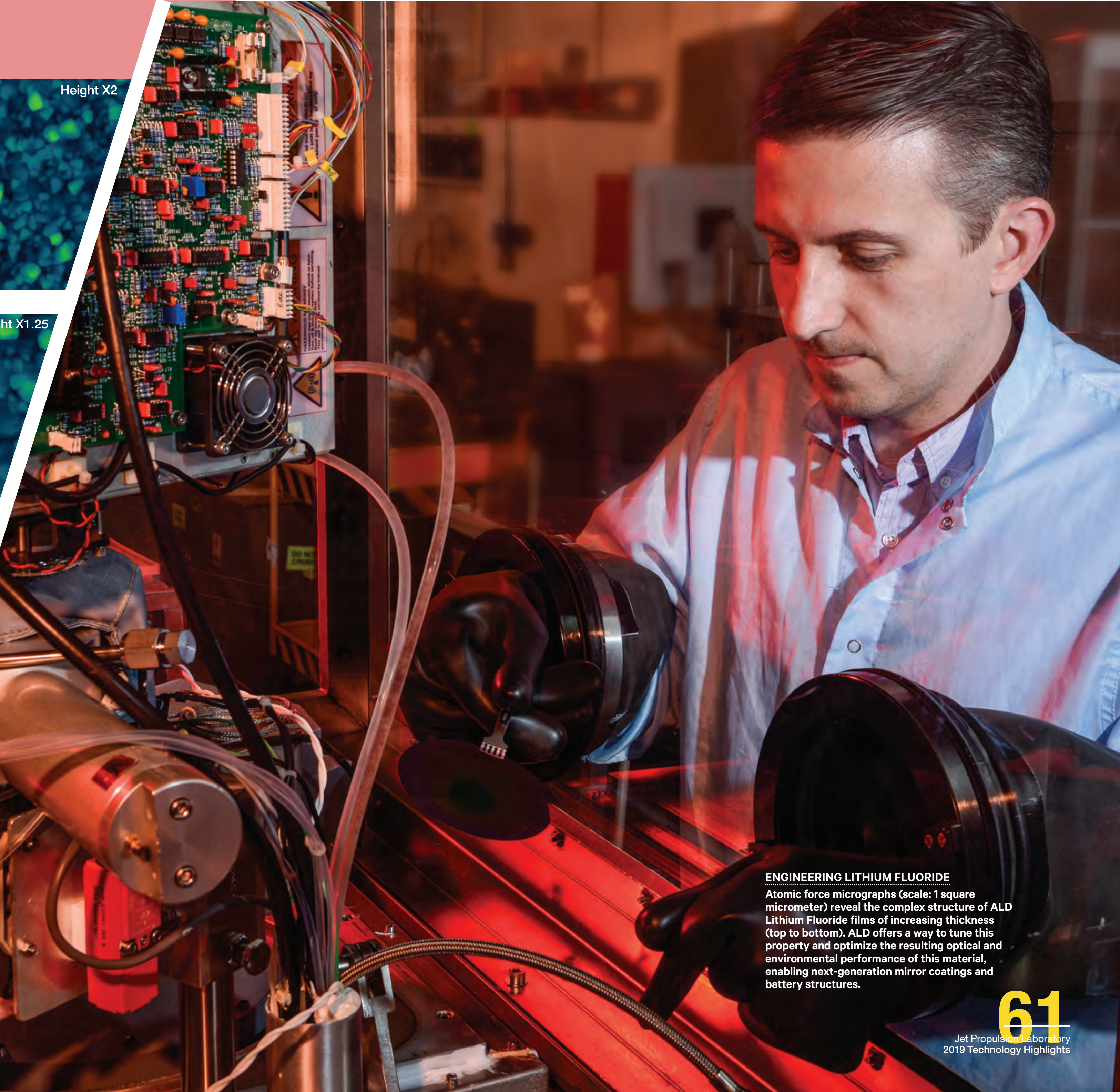
Recently, new ALD processes have been demonstrated to deposit metal fluoride materials at temperatures as low as 100°C. Metal fluoride materials possess good optical properties for observing deep ultraviolet light. The new process pulses anhydrous hydrogen fluoride and various organometallic compounds. Different materials have different properties and reactions, so this same technique can also result in the thermal ALE of some materials. Investigation of a special case of this fluorination-ALE method to improve etch rates, reduce processing temperature, and improve selectivity has led to immediate applications. For example, this combination of ALE and ALD is used to gently remove the native oxide from metallic aluminum and replace it with other materials for a variety of optics and sensing applications.

Various ultraviolet applications are already been produced for use in missions. Mirror coatings using this technology have been provided to the University of Colorado Boulder and Goddard Space Flight Center's SISTINE mission, as well as the SPRITE CubeSat. Solar-blind imaging sensors, or cameras that are unaffected by sunlight, have also been developed and are planned for delivery to the University of Arizona and Arizona State University for their respective ultraviolet wavelength missions.

These atomic scale processes are also relevant to energy storage applications. JPL is exploring the use of these coatings in Lithium-ion battery technology as a building block toward future work in all-solid-state battery systems. Solid state batteries are expected to be much more efficient than current technology, and could help unlock many green technologies currently limited by inefficient energy storage. It is also worth noting they are nonflammable. /

ALTERING COMPONENTS AND MATERIALS AT THE ATOMIC LEVEL IS MAKING INSTRUMENTS AND SENSORS OF ALL CLASSES MORE CAPABLE BY ELIMINATING MINISCULE YET IMPACTFUL IMPERFECTIONS





ENGINEERING LITHIUM FLUORIDE

Atomic force micrographs (scale: 1 square micrometer) reveal the complex structure of ALD Lithium Fluoride films of increasing thickness (top to bottom). ALD offers a way to tune this property and optimize the resulting optical and environmental performance of this material, enabling next-generation mirror coatings and battery structures.

EYE OF THE STORM

This is one of the first images captured by TEMPEST-D, showing Hurricane Florence over the Carolinas. Larger volumes of more recent weather data can help communities prepare for extreme weather.

A NEW RADAR GIVES SMALL SATELLITES CAPABILITY ONCE RESERVED FOR LARGE SYSTEMS

FIRE THE CUBESATS

This photo shows CubeRRT and Tempest-D being deployed from the International Space Station on July 13, 2018. Small satellites can fit as an extra payload on other missions: these two launched with several other small satellites aboard a Space Station resupply mission.

SCIENCE CUBED

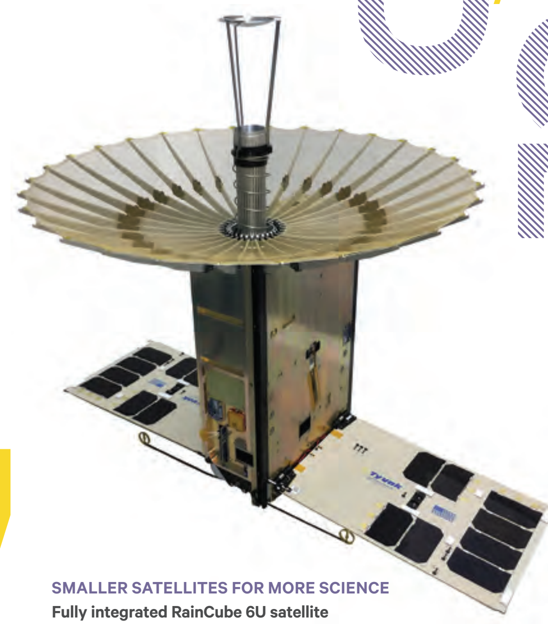
Small, standardized, , modular, inexpensive satellites, like CubeSats, have long promised to change the space sector. Thanks to a new radar, they have matured as competent platforms for Earth Science missions in low Earth orbit (LEO). Previously, the small size and power restrictions of CubeSats prevented them from contributing meaningful science data at the level of larger missions; fundamental instruments just could not fit or be powered. Newly developed radar, antennas, and associated subsystems that fit on a CubeSat with power restrictions low enough to provide science-quality capability. Several technology demonstration missions have been enabled by this breakthrough. RainCube, TEMPEST-D, and CubeRRT all launched in 2018 and have successfully validated their technologies. These missions center on water in the atmosphere; i.e., clouds, from convection to precipitation. Because clouds represent a significant gap in our understanding of weather, knowing them at a global scale is a key target, identified by the Earth Science community's Decadal Survey.

Radar in a CubeSat (RainCube) is the first ever demonstration of a radar instrument in a CubeSat. RainCube developed a 35.75 GHz Ka-band radar payload and an ultra-compact lightweight deployable Ka-band antenna. Following a successful deployment from the International Space Station in July 2018, the RainCube radar was turned on in late August, and has been successfully acquiring vertical range profiling measurements of precipitation and land surface since then, well beyond the mission life requirement.

CloudCube, a relative of RainCube, flew on a technology demonstration mission in September 2018. This new radar was enabled by a compact power amplifier capable of fitting on a small satellite. CloudCube will be able to operate on three frequencies: Ka-, W-, and G-band. For TEMPEST-D, JPL developed a mm-wave radiometer payload that operates at five channels. The CubeSat Radiometer Radio Frequency Interference Technology Validation (CubeRRT) was selected to demonstrate on-board, real-time radar frequency interference processing. It has three critical pieces of technology: a wideband antenna unit, a radiometer front-end unit, and a radiometer digital back-end that performs the on-board detection and filtering of interference.

Numerical climate and weather models depend on measurements from space-borne satellites. Precipitation-profiling capabilities are currently limited to a few instruments deployed in LEO, which cannot observe the evolution of weather phenomena on a time scale of minutes. Looking toward the future, a constellation of precipitation-profiling instruments in LEO would provide this essential capability within budget constraints. Such a constellation would revolutionize climate science and weather forecasting.

CONSTELLATIONS OF INEXPENSIVE SATELLITES WILL PROVIDE THE CLEAREST UNDERSTANDING OF OUR PLANET AND ITS WEATHER



SMALLER SATELLITES FOR MORE SCIENCE

Fully integrated RainCube 6U satellite including the solar panels and the deployed radar antenna. Several satellites like RainCube could operate over different parts of the Earth at the same time to gather near real-time weather information.

TIMING IS EVERYTHING

THE FARTHER WE GO, KNOWING WHEN YOU ARE BECOMES KEY TO KNOWING WHERE YOU ARE

DESIGNING TIME
This computer-aided design (CAD) drawing shows the payload that flew on Space Test Program-2: the Deep Space Atomic Clock. It is now operating on orbit.

Time is not only a fundamental fact of our existence; we rely on precise timekeeping like never before. All our automated processes, like financial transactions, navigation, and science rely on knowing what time it is—down to the microsecond, or one millionth of a second. Most financial transactions are automated, and without timekeeping accuracy at the level provided by atomic clocks, the system would fail completely. The same is true of a spacecraft trying to navigate far from Earth, particularly if we want it to do so autonomously. The lack of highly stable, miniaturized timekeeping systems has been a roadblock to this kind of capability.

The Deep Space Atomic Clock, or DSAC, is a technology demonstration of a small, ultra-precise, mercury-ion atomic clock. It was launched into Earth orbit on June 25, 2019 to test its potential as a next-generation tool for spacecraft navigation, radio science, and global positioning systems. The technology is designed to improve navigation of spacecraft to distant destinations and enable collection of more data with better precision, and should be up to 50 times more stable than today's best navigation clocks.

In a laboratory setting, DSAC's precision has been refined to permit no more than 1 nanosecond of drift, or one billionth of a second, in 4 days. DSAC is the first timekeeping device stable and accurate enough to chart a spacecraft's path that is also small enough to fit onboard.

Ground-based atomic clocks have been critical to most deep-space vehicle navigation for the same reason a space-based one is being developed: the timing data they provide is necessary for precise positioning, which in turn is needed for precise navigation. Just as modern GPS uses one-way signals to enable terrestrial navigation services, DSAC will provide the same capability in deep-space—with such extreme accuracy that researchers will need to carefully account for the effects of relativity as impacted by gravity, space and time. Clocks in GPS-based satellites, for example, must be corrected to account for this effect, or their navigational fixes begin to drift.

DSAC's technology demonstration mission is planned to continue for one year in low-Earth orbit. The clock will use GPS signals to demonstrate precision orbit determination and confirm its performance. This technology development is a enabling the development of deep-space autonomous radio navigation.

DEEP SPACE ATOMIC CLOCK (DSAC) IS TESTING A NEW TIMEPIECE FOR DEEP SPACE NAVIGATION, WITH IMPACTS ACROSS THE ECONOMY

DEEP SPACE ATOMIC CLOCK

This image shows DSAC being installed. Accurate time keeping on spacecraft is essential to synchronizing communications needed to operate spacecraft at increasingly large distances.

TIME AND NAVIGATION

Because distance equals velocity multiplied by time, the distance between a ground station and a spacecraft is the time it takes for a transmission to flow between them multiplied by the speed of light. Over large distances, gravity begins to affect time, which is why more accurate clocks are needed for deep space missions.

LEARNING TO FLY
This image shows the Hexacopter and test vehicle with payload during a field test in the Arroyo. The technology met or exceeded most of its performance goals, even being able to tell its shadow from other features in its field of view.

HYBRID SYSTEMS
Principal Investigator Teddy Tzanetos inspects the Hexacopter Testbed's avionics system and sensor suite. Getting these state-of-the-art systems to work well with commercial technology was a challenge in and of itself, but one that could lead to new mission designs to enable more missions with fewer resources.

THE HEXACOPTER TESTBED PROJECT IS VALIDATING HOW TO MAKE MACHINES NAVIGATE WITH INTELLIGENCE

Technology development for space missions can sometimes take longer than it does in other fields because of the only-one-shot nature of most space exploration and science missions. Other times, it can cost more than expected. Always, space science and exploration platforms are limited by size, weight, power, and cost. Thinking outside the box of traditional technology development, technologists are combining their highly refined systems on commercial off the shelf (COTS) products. This provides two specific benefits. Firstly, technology development is made faster, and more affordable, allowing for rapid improvement of a technology by rebuilding it several times. Secondly, some missions are only made possible by the speed and low cost of this approach. This will be even more relevant to fields where commercial investment far exceeds Government's, like artificial intelligence.

The Hexacopter Testbed Project is an example of this kind of development. State-of-the-art navigation algorithms, avionics systems, and flight software, are combined with COTS hardware. The system incorporates vision-based navigation and autonomous feature detection and tracking. JPL conducted a joint field test of the Hexacopter airborne testbed in collaboration with Caltech's Center for Autonomy Systems and Technologies. Together, they assessed the real-time performance of JPL's navigation algorithms, then identified and solved non-real-time Linux challenges inherent to navigation algorithms operating on such a system. The navigation system was able to move up to 13.96 meters per second, demonstrate take-off, hovering, flight over 200m from starting point, and met or surpassed its accuracy performance goals. The feature tracking system was advanced to the point of being able to distinguish its own shadow and legs from features in the environment.

Working with COTS products presents its own challenges however. Getting highly refined advanced technology like JPL's to work with far less sophisticated systems presented multiple challenges, such as the non-real-time operating software. Addressing those challenges however will significantly expand the potential impact of many missions capable of incorporating COTS computer systems—with their unique trade-offs —to low-cost missions for Mars, Earth, or other low-radiation environments like Venus' atmosphere.

Future deployments of mixed commercial –JPL hardware and algorithms will make more affordable, frequent, and in some cases more capable missions. These architectures will only be viable through leveraging the advancements of commercial industry, where Linux-based operating systems are just one example. "Failing fast and cheap" is an approach that provides an alternative to longer term, more deliberate technology advancement pathways. Ultimately, the Hexacopter Testbed Project shows the value of both approaches has more potential than either strategy alone.

SYSTEM AUTONOMY ENABLED BY ARTIFICIAL INTELLIGENCE HAS OPENED UP A NEW PARADIGM OF RAPIDLY EVOLVING TECHNOLOGY FOR NEW LOW-COST PLATFORMS

UNDER A HEX

DIG THIS

REINVENTING THE CUTTING EDGE

Destinations with high value science are often difficult to reach in more than one way. Once a robotic mission reaches its goal, and is able to survive the extreme cold, heat and radiation, then collecting a sample for analysis can be a challenge. Thick ice on outer moons, like Europa or Enceladus, can be challenging to cut. Fine lunar regolith can get caught in machinery and stall operation. Additive manufacturing is being used to address these material and component challenges. Specifically, in the creation of new excavation tools with unique properties for space science missions.

Additive manufacturing, also known as 3D printing, makes an object from a computer-aided design model by depositing layers of material. Traditional manufacturing is known as subtractive because material is removed from a stock, like carving a statue out of a block of marble. Additive manufacturing enables forms impossible to create with subtractive methods, including complex geometries and gradual transitions of different composite materials.

One example of these additively manufactured blades has a self-hammering effect that acts like a percussive drill. It can both cut through off world ice more effectively, and with less strain on the blade, making it less likely to break during operation.

Additive manufacturing techniques can also provide new ways of acquiring scientific data. A cutting tool can be used to determine fundamental mechanical properties of what it is cutting using embedded porous regions, or holes, to diffuse gasses or liquids during excavation. This could then be analyzed by spectrometers or other tools. The first mechanical tests on a variety of new 3D-printed metal alloys were performed, including tool steel, bulk metallic glass, Inconel metal matrix composites, and titanium/titanium-carbide composites.

These excavation tools were originally developed to cut ice, but the same principles can be applied to rock as well. This work is adaptable for any platform that will trench, drill, or excavate in ice, rock, or loose regolith. The cutting tools can be developed in metal alloys compatible for different environments, with designs suitable for any type of lander.

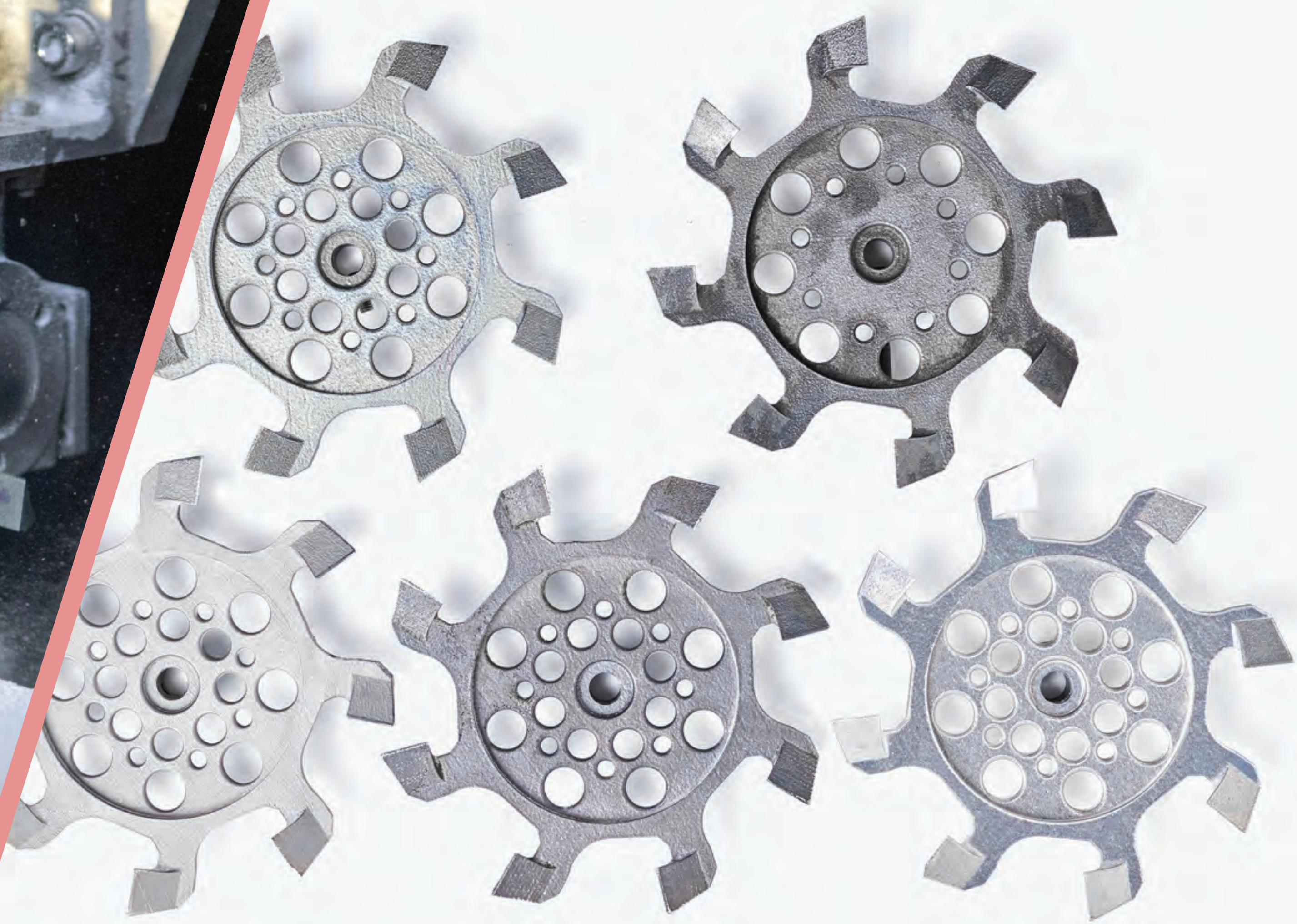
This could allow chemical compositions to be measured without an additional, specialized sampling and delivery system, greatly reducing sample handling complexity. This technology could help maximize science output from a lightweight lander to a comet, for example.

This technology also has applications in fields like mining and oil extraction. Similar experimentation with additively manufactured components will show more scientific opportunities. The designs of the compliant blades and the instruments resulted in two provisional patents with Caltech.

ADDITIVELY MANUFACTURED EXCAVATION TOOLS ALLOW MORE COMPLEX DESIGNS AND OFFER OPPORTUNITIES TO BE EMBEDDED WITH COMPONENTS

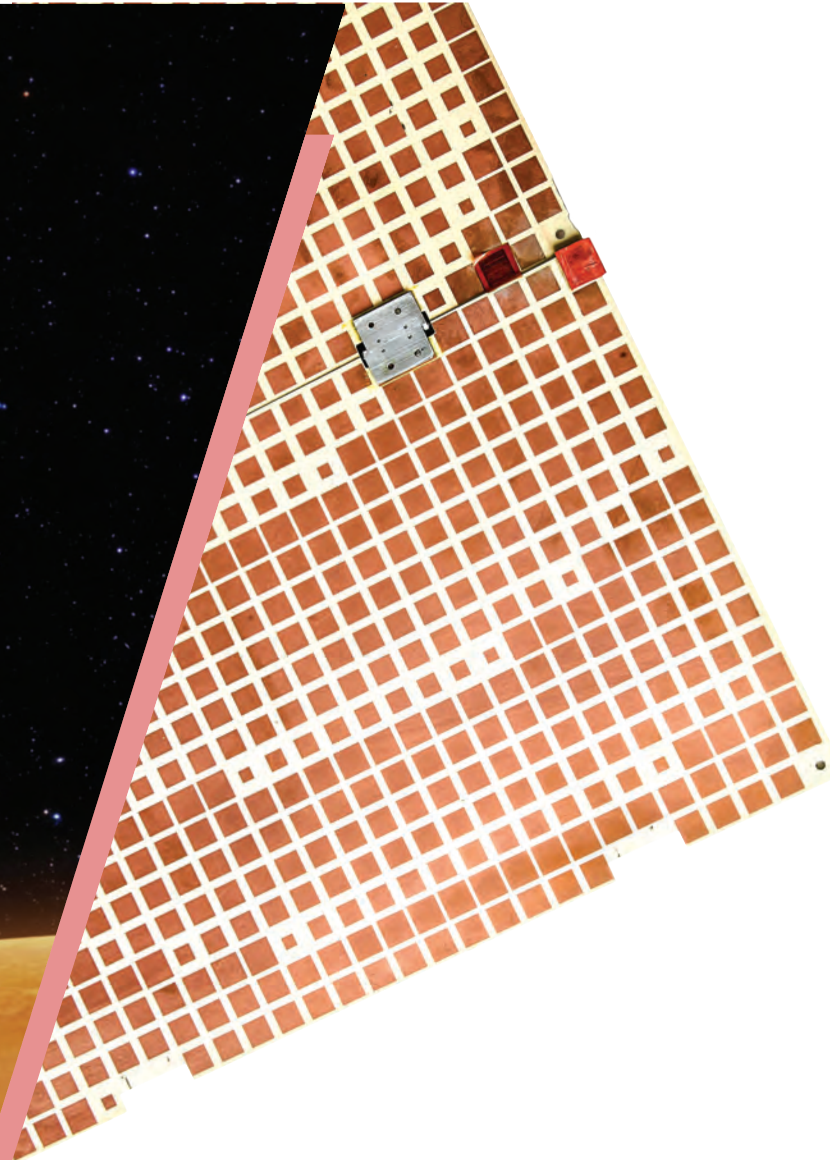
LIVE TEST

Right: A live test of the 3D printed blades on salt blocks meant to simulate Europa's much denser, thicker, and difficult to cut ice than what we see naturally here on Earth. Below: A drill tip specially printed core through tough ice, but also contains porous regions in the walls to gather particles and analyze them while drilling.



BLADES DESIGN

Blades of different metals can be printed to create new capabilities. These blades are designed to trench through ice with unknown characteristics.



MarCO

A closeup of MarCO's reflectarray, and illustration of their travel from Earth for a Martian flyby during InSight's landing.

THE DAWN OF A NEW PARADIGM IN EXPLORATION

Mars Cube One is a duo of twin satellites often referred to as "the MarCOs." CubeSats are a class of spacecraft based on a standardized small size and modular use of off-the-shelf technologies. Many have been made by university students, hundreds have been launched into Earth orbit, often using extra payload mass available on launches of larger spacecraft, but only one mission took them to another planet. Launched with the most recent Mars mission, Insight, the MarCOs provided the communications relay for Insight's interplanetary landing in real-time. Past Mars missions have relied on large spacecraft already in Mars orbit for relay during landing—MarCO represent a first-of-a-kind, "bring your own" approach.

The two CubeSats separated from the Atlas V booster after InSight's launch, then traveled independently along their own trajectories to the Red Planet, which leveraged JPL's expertise in interplanetary trajectory planning, communication, guidance, control, and navigation.

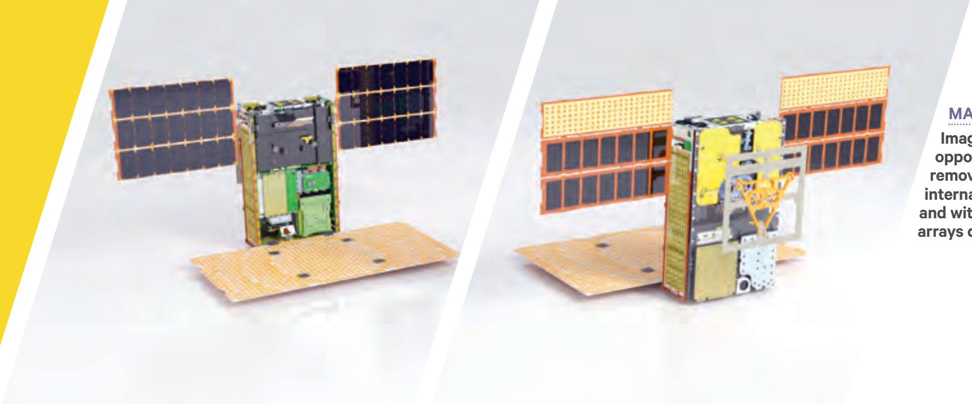
During InSight's entry, descent and landing (EDL) operations, the lander transmitted information in the UHF radio frequency band to both the MarCOs and NASA's Mars Reconnaissance Orbiter (MRO) flying overhead. MRO stored the data for transmission to earth several hours later, but MarCO's softball-size radio provided via X-band EDL information to mission control immediately.

MarCO's success depended on its JPL-invented flat reflectarray antenna. Reflectarray was first proven in March 2018 on the Integrated Solar Array and Reflectarray Antenna (ISARA) mission in Earth orbit.

MARCOS POLO

Reflectarray is based on a new approach: an array of printed circuit board patches of varying sizes. The reflecting surfaces used in these antennas can be designed to produce many different radiation patterns. Reflectarrays are exceptionally versatile and can be easily tailored to meet unique mission requirements, including complicated mission tasks such as scanning interferometry. The success of MarCO allows for a "bring-your-own" communications relay satellite option for future surface missions in the critical few minutes between atmospheric entry and touchdown.

NASA, JPL will set another milestone with history's first CubeSat to orbit another celestial body: Lunar Flashlight will chart the far and near side of the Moon, becoming the first CubeSat to use green, environmentally friendly propellant, and the first to use lasers to look for water ice. This mission will help resolve an important knowledge gap when it comes to living and working on the Moon, like where the water is and how much of it there is.



MARS CUBE ONE

Images of MarCO's two opposite sides, with cover removed to show some internal components, and with antennas and solar arrays deployed.

WE SUCCESSFULLY COMPLETED THE FIRST CUBESAT MISSION IN HISTORY TO GO TO ANOTHER PLANET

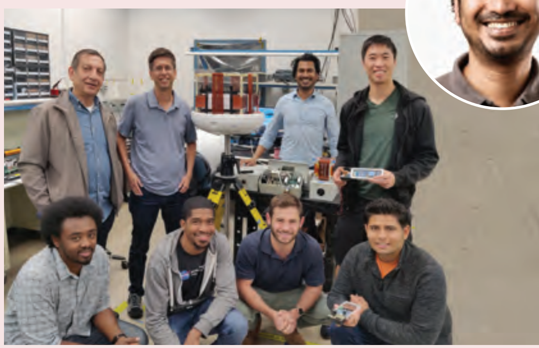
CONTRIBUTORS PROFILES

DARMINDRA ARUMUGAM | pg 44

Principal Investigator, POINTER

Dr. Arumugam performs research in applied electromagnetics with emphasis on radio propagation and scattering, radar sounding systems, localization techniques, and low-frequency or quasi-static electromagnetic fields. He is the Supervisor of the Radar Concepts and Formulation Group.

Pictured left to right first row: Raffi Ekizian, Peter Littlewood, Darmindra Arumugam, Nicholas Peng; second row: Brook Feyissa, Jeffrey Burton, Jack Bush, Divyam Mishra (student); not pictured: Steve Carnes



CHRISTOPHER ASSAD | pg 52

Principal Investigator, BioSleeve

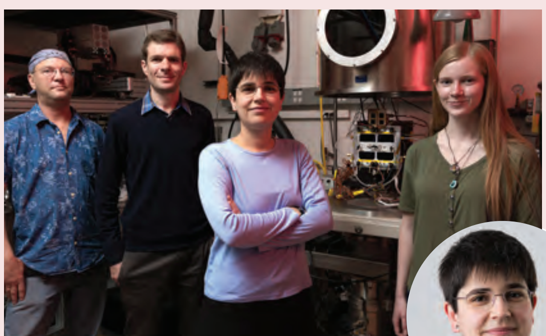
Dr. Assad performs research on human-machine interfaces and bio-inspired robotics as a Robotics Technologist, in the Mobility and Robotics Systems Section.

Pictured left to right: Chris Assad, Sherrie Hall, Viet Nguyen, Michael Wolf, Jaakko Karras; not pictured: Adrian Stoica, Viet Nguyen, Thomas Fuchs, Jason Carlton, Jacob Tims, Dima Kogan, Gerik Kubiak

BOB BALARAM | pg 08

Principal Investigator, Mars Helicopter

Dr. Balaram is a Robotics Technologist. JPL Team: H. Grip, M. Aung, J. Ravich, T. Tzanetos, J. Karras, D. Zhu, M. Smart, G. Carr, S. Dawson, T. Canham, R. Stern, B. Whitaker, M. Pauken, S. Cappucci, A. Quon, C. Lefler, G. Kubiak, M. Starch, J. Lam, J. Melko, K. Lee, J. Umland, M. Kokorowski, T. Bailey, L. Leach, C. Duncan, S. Stride, L. McNally, M. Chase, P. Meras, G. Massone, C. Liebe, B. Burns, D. Fugett, A. Nuss, K. Beckwith, B. Shirey, S. d'Agostino, D. Bayard, J. Delaune, R. Brockers, J. Fernandez, E. Konefat, F. Mier-Hicks, R. Smith, J. Zitkus, P. Hurst, T. Ngo-Luu, R. Ybarra, J. Koehler, L. Matthies, J. Maki, M. Golombek, T. Nugyen, T. Kopf, D. Bell, N. Ferraro, J. Seastrom, D. Lewis, C. Nugyen

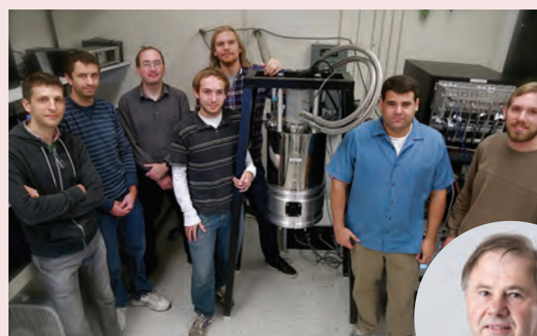


ANDREEA BOCA | pg 54

Principal Investigator, Deep Space Solar Cells

Dr. Boca is a Systems Engineer in the Solar Array Engineering and Technology Group. For the past 12 years she has led a variety of technology development projects in space photovoltaics, with a focus on extreme environments ranging from the Sun's corona to the moons of Saturn.

Pictured left to right: Bob Kowalczyk, Jonathan Grandidier, Andreea Boca, Clara MacFarland; not pictured: Molly Shelton

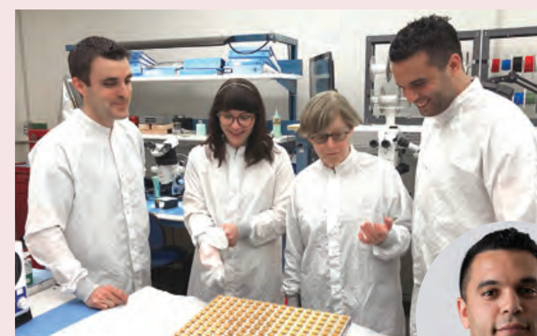


BRUCE BUMBLE | pg 14

Co-Investigator, UVOIR Microwave Kinetic Inductance Detectors for Astrophysics

Dr. Bumble is a Senior Engineer in the Superconducting Materials and Devices Group at JPL's Microdevices Lab. He provided the Principal Investigator with the MKIDs needed to perform this astrophysics research.

Pictured: Principal Investigator and UCSB Professor Ben Mazin (in blue) with his team. At JPL this project has received contributions from Byeong Ho Eom, Peter Day, and Henry G. LeDuc



NACER CHAHAT | pg 22

Principal Investigator, Europa Lander Antenna

Dr. Chahat is part of the Flight Communications Systems Section's Technical Staff. Nacer has developed and infused multiple successful antenna technologies on RainCube, MarCO, SWOT, Mars Helicopter, Psyche, and a potential Europa Lander mission.

Pictured left to right: John Luke Wolf, Heather Lim, Polly Estabrook, Nacer Chahat; not pictured: Luz Maria Martinez Sierra, James Chinn, Brant Cook

CONTRIBUTORS PROFILES

KEN COOPER | pg 16

Project Lead, VIPR

Dr. Cooper is a Radio Frequency Microwave Engineer in the Submillimeter Wave Technology Group. His work focuses on security and science applications.

Pictured left to right: Raquel Monje, Matt Lebsock, Bob Dengler, Ken Cooper, Ricky Roy, Maria Alonso, William Chun, and Robert Lin; not pictured: Jose Siles, Chaitali Parashare, Luis Millan, Ian Mccubbin, Barron Latham, Marco Hernandez

TODD ELY | pg 64

Principal Investigator, DSAC

Dr. Ely is a Navigation Engineer in the Mission Design and Navigation System Engineering Group

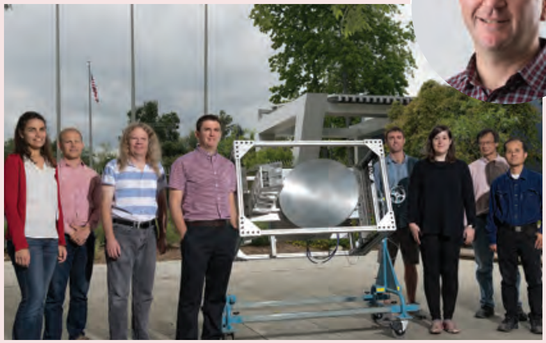
Eric Burt, Angela Dorsey, Todd Ely, Daphna Enzer, Randy Herrera, Da Kuang, Patricia Lock, David Murphy, John Prestage, David Robison, Michelle Rowe, Ela Seal, Jill Seubert, Jeffrey Stuart, Joseph Stuesser, Robert Tjoelker, Rabi Wang. Pictured are Tom Cwik and former DSAC Project Manager Allen Farrington

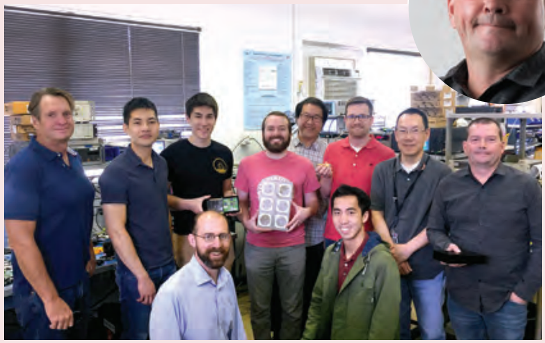
GARTH FRANKLIN | pg 32

Deputy Project Manager for NTS-3

Garth Franklin is the Supervisor of the Advanced Radiometric and Gravity Sensing Instruments Group. He is responsible for Cion, the software-enabled GPS radio occultation system.

Pictured left to right, back to front: Steve Lowe, Myron Lee, Devin Cody, Kameron Larsen, Byron Iljima, Chad Galley, Jeff Tien, Garth Franklin, David Robison, Jehhal Liu; not pictured: Tom Meehan, Jacob Gorelik





MATTHEW GILDNER | pg 34

Principal Investigator, AquaSimian

Matthew Gildner is a Robotics Mechanical Engineer in the Mobility and Robotic Systems Section, and Team Lead of the Mars Science Laboratory Operations Rover Planning Team.

Pictured from left to right: Justin Koch, Matt Gildner, Renaud Detry, Torkom Pailevanian, Dan Levine; not pictured: Mike Garrett and Chris Yahnker

JOHN HENNESSY | pg 60

Principal Investigator, Atomic Layer Engineering for UV Materials and Systems

Dr. Hennessy is a Technologist at JPL's Microdevices Laboratory. His current research interests include the development of ALD/E processes for optical and electronic applications related to UV detector-integrated filters, UV reflective coatings, and materials interface engineering.

Pictured: April Jewell, Shouleh Nikzad, Michael Hoenk, Charles Shapiro, Alex Carver, Sam Cheng, Doug Bell, Bruce Hancock, Matt Dickie, Todd Jones, Tim Goodsall; not pictured: John Paul Jones, Kunjithapatham Balasubramanian

DOUGLAS HOFMANN | pg 68

Principal Investigator, 3D Printed Robotic Excavation Tools and Instruments

Dr. Hofmann is a Technologist in the Materials Development and Manufacturing Group, Principal Investigator of NASA's Fabrication of Amorphous Metallic glass In Space (FAMIS) Project, and leads research in bulk metallic glasses and metal 3D printing.

Pictured left to right: Morgan Hendry, Cecily Sunday, Mitchell Watson; not pictured: Phillipe Tosi, Samad Firdosy, Andre Pate, Christopher Yahnker

CONTRIBUTORS PROFILES

SONA HOSSEINI | pg 12

Principal Investigator, HOLMS Mini Spectrometer

Dr. Hosseini is a planetary scientist and an instrument developer who is researching the role of water in Solar System formation and evolution. She has led numerous studies to simulate and study low-density gas environments in our solar system.

Pictured left to right: Kalind Carpenter, Gregory Peters, Sona Hosseini, Yen-Hung Wu; not pictured: Luis Phillipe Tosi, Jacob Clarke, David Jung

PEKKAA KANGASLAHTI | pg 42

High Resolution Microwave Radiometer (HRMR)

Dr. Kangaslahti is Supervisor of the Microwave Systems Technology Group. His team has successfully assembled and tested HRMR for the Jason-CS mission.

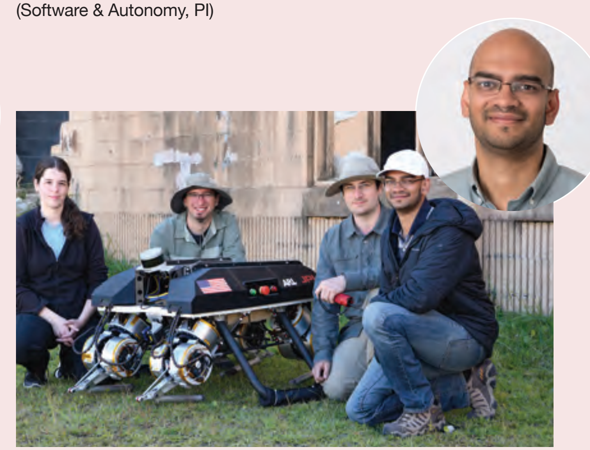
Left to right: Pekka, Isaac Ramos, Sharmila Padmanabhan, Hamid Javadi, Heather Lim, Mary Soria and Shannon Statham. Not pictured: Oliver Montes, Alan Tanner, Erika Hernandez, Arlene Baiza, Marco Chavez, Shant Muradian

SISIR KARUMANCHI | pg 20

Principal Investigator, Llama Robot

Dr. Karumanchi is a Robotics Technologist in the Robotic Manipulation and Sampling Group; his focus is on robotic systems that interact with unstructured and uncertain environments.

Jay Jasper (Design & Integration Lead), Ara Kourchians (Power Electronics Lead), Blair Emanuel (Mechanical & Test Support), Kyle Edelberg (Software Support), John Koehler (Electrical Support), Brett Kennedy (Supervision), Sisir Karumanchi (Software & Autonomy, PI)



ANDREW KLESH | pg 70

Chief Engineer, Mars Cube One (MarCO)

Dr. Klesh is a Systems Engineer in the Mission Concept Systems Development Group. He is also the Principal Investigator on Glacial Moulin Mapping Using Robotic Submersible and technical lead for the Buoyant Rover for Under Ice Exploration.

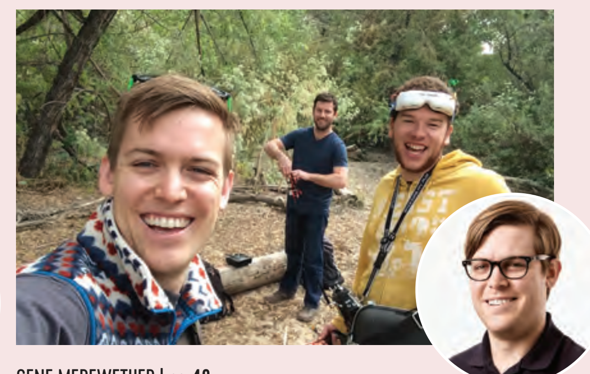
Brian Clement, Cody Colley, Peter DiPasquale, John Essmiller, Robert Fogg, Daniel Forgette, Peter Ilott, Andrew Klesh, Michael Kobayashi, Joel Krajewski, Anne Marinan, Tomas Martin-Mur, Joel Steinkraus, David Sternberg, Thomas Werne, Brian Young

WILLIAM KLIPSTEIN | pg 10

Instrument Manager, Laser Ranging Interferometer (LRI)

Dr. Klipstein was succeeded by Dr. Kirk McKenzie as LRI Instrument Manager. Dr. Klipstein is currently the Project Manager for Deep Space Optical Communication.

JPL Team: A. Abramovici, B. B. Okihiro, D. C. Barr, M. P. Bize, M. J. Burke, K. C. Clark, G. de Vine, J. A. Dickson, S. Dubovitsky, W. M. Folkner, S. Francis, M. S. Gilbert, M. Katsumura, K. Larsen, C. Christian Liebe, J. Liu, P. R. Morton, A. T. Murray, D. J. Nguyen, J. A. Ravich, D. Shaddock, R. Spero, G. Spiers, A. Sutton, J. Trinh, D. Wang, R. T. Wang, B. Ware, C. Woodruff



GENE MEREWETHER | pg 48

Principal Investigator, TORQ

Gene Merewether works on flight software for Mars Helicopter, leads software efforts for next-generation Martian rotorcraft, and for multirobot aerial vehicle capabilities for JPL's DARPA Subterranean Challenge team.

From left to right: Gene Merewether, Rob Reid and Thomas Paynter (intern from the Curtin University in Perth, Western Australia).

CONTRIBUTORS PROFILES

RUDRANARAYAN MUKHERJEE | pg 58

Principal Investigator, REMORA CubeSat Arm

Dr. Mukherjee is a Research Technologist and Group Leader in the Robotics Modeling and Simulation Group. Other research interests include Vehicle Terrain Interactions, Autonomy for high-DOF motion planning and coordinated control, and Scientific Computing.

Ryan Mccormick, Spencer Backus, Renaud Detry, Timothy Setterfield, Alex Austin, Kristopher Wehage, ASU Professor Heni Ben Amor, Interns and Graduate Students

AMIR RAHMANI | pg 28

Principal Investigator, Swarm Autonomy

Dr. Rahmani is a Robotics Systems Engineer in the Maritime and Multi-Agent Autonomy Group. He is also the NASA Small Business Technology Transfer (STTR) subtopic manager on coordination and control of swarms of space vehicles.

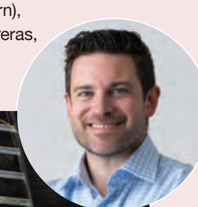
Pictured left to right, standing: Dr. Amir Rahmani (JPL), Dr. Soon-Jo Chung (Caltech); first row: Dr. Wolfgang Hoenig (Caltech), Elena Sorina Lupu (Caltech), Becca Foust (Caltech), Benjamin P. Riviere (Caltech), Dr. Kyunam Kim (Caltech); second row: Dr. Vincenzo Capuano (Caltech), Dr. Ryan Alimo (JPL), Kai Matsuka (Caltech); third row: Hiroyasu Tsukamoto (Caltech), Yashwanth Kumar Nakka (Caltech); missing from JPL: Dr. Changrak Choi, Dr. Adrian Stoica, Dr. Michael Wolf, and Dr. Reza Karimi

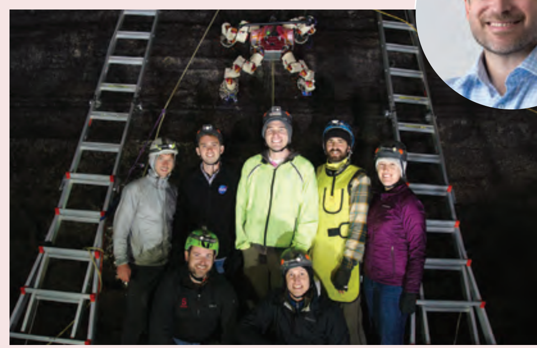
AARON PARNESS | pg 56

Principal Investigator, Climbing Robots

Dr. Parness develops climbing robots and robotic grippers that use claws, drills, electrostatics, and gecko-like adhesives to stick to their surroundings.

Pictured, back row, left to right: Aaron Curtis (Both), Jeremy Nash (Both), Neil Abcouwer (LEMUR), Kyle Uckert (LEMUR), Christine Fuller (LEMUR); front row, left to right: Aaron Parness (Both), Renaud Detry (LEMUR); LEMUR team not pictured: Russell Smith, Eric Contreras, Carolyn Parcheta, Mircea Badescu, Jonathan King (intern), Theodore Kern (intern); IceWorm team not pictured: Shoya Higa, Ian Rankin (intern), Steven Morad (intern), Blair Emanuel, Russell Smith, David Kim, Eric Contreras, Vladimir Arutyunov, John Hochschild (intern), Matt Martone (intern)





UMAA REBBAPRAGADA | pg 40

Point Source Real-Bogus Lead, ZTF Machine Learning

Dr. Rebbapragada is a Data Scientist in the Machine Learning and Instrument Autonomy Group. Her work is focused on the infusion of state-of-the-art techniques from the machine learning community into large-scale data science systems, with a current focus on astronomical surveys.

Above left to right: Tomas Ahumada (UMD), Nadeja Blagoradnova (Caltech), Frank Masci (IPAC/Caltech), Sara Frederick (UMD), Brian Bue (JPL), Charlotte Ward (UMD); below left to right: Richard Walters (Caltech), Ashish Mahabal (Caltech), Dmitry Duev (Caltech)

EVA PERAL | pg 62

Principal Investigator, RainCube

Dr. Peral and her team are working on innovative approaches to miniaturize the radar electronics and ultimately reduce the cost of radar space missions.

Pictured front row: C. Parashare, A. Babuscia, S. Joshi, S. Statham, E. Merida, M. Cruz, C. Abesamis; second row: T. Imken, M. Vining, J. Zitkus, S. Tanelli, R. Rebele, M. Soria, A. Baiza; third row: N. Chahat, J. Sauder, S. Gibson, G. Cardell, B. Ortloff, B. Wang, T. Bailey, D. Chi; back row: B. Custodero, D. Price, J. Kanis; not pictured: G. F. Sacco; O. Sy, S. Marroquin, S. Carlson, C. Farguson, K. Lo, S. Orellana, M. Ramsey, N. Rouse, M. Tran, D. Wang, R. Beauchamp, D. Escoto, R. Guerrero, B. Kahn, V. Vorperian, W. Sokolowski, C. Stell

RAQUEL RODRIGUEZ MONJE | pg 62

Principal Investigator, Cloud Cube

Dr. Rodriguez Monje is an Instrument System Engineer in the Radar Concepts and Formulation Group, developing next generation compact millimeter wave radars. She is also a core team member of DopplerScatt, VIPR and GAISR technology projects.

Pctired: Rob Beauchamp and Raquel Rodriguez Monje; not pictured: Ken Cooper (co-I), Matthew Lebsock (co-I), Simone Tanelli (co-I), Shivani Joshi, Chad Baldi (co-I), Chaitali Parashare, Amelia Asamoto

CONTRIBUTORS PROFILES

SEUNGWON LEE | pg 30

Climate Model Diagnostic Analyzer (CMDA)

Dr. Lee serves as the principal investigator for several NASA research projects and the technical supervisor of the Science Data Modeling and Computing group.

Pictured left to the right: Kay Suselj, Seungwon Lee, Benyang Tang (behind S. Lee), Huikyo Lee, Jinbo Wang, John T Reager, Lei Pan, Chengxing Zhai, Terry Kubar

JOSE V. SILES | pg 24

Principal Investigator, Multi-Pixel Terahertz LO Sources

Dr. Siles is Principal Investigator of several NASA funded programs to develop high-power Terahertz local oscillator sources and array receivers. Dr. Siles also led the LO system of NASA's Stratospheric THz Observatory (flown in 2016/2017).

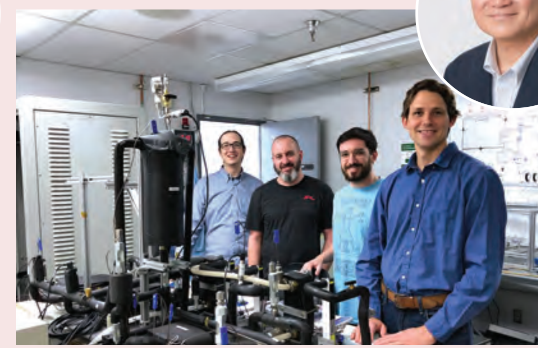
Jose Siles, Jonathan Kawamura, Choonsup Lee, Darren Hayton, Robert Lin, Ken Cooper, Alejandro Peralta

ERIC SUNADA | pg 38

Principal Investigator, Two-Phase Thermal Control Technologies

In addition to performing research on advanced multi-phase thermal control systems, Mr. Sunada coordinates the strategic roadmap for JPL's thermal management portfolio and paths for infusion. His focus is on those technologies which enable missions to extreme environments with tomorrow's high performing spacecraft.

Benjamin Furst, Stefano Cappucci, Takuro Daimaru, Scott Roberts



ADRIAN TANG | pg 26

Principal Investigator, CMOS Spectrometers

Dr. Tang obtained his PhD from UCLA in electrical engineering and is leading work at JPL focused on infusing

CMOS system-on-chip technology from the gaming and mobile phone markets into spaceflight instruments. Adrian is an active contributor to many IEEE publications in the solidstate circuits and microwave integrated circuit areas.

THEODORE TZANETOS | pg 66

Principal Investigator, Hexacopter Testbed Project

In addition to his work with the Hexacopter Testbed, Teddy serves as the Mars Helicopter Flight Test Conductor and Electrical Ground Support Equipment Lead. He is also the Principal Investigator for the Mars Science Helicopter.

Pictured left to right: Lucas Leach, Josh Ravich, and Fernando Mier-Hicks; not pictured: Dave Bayard, Dylan Conway, Roland Brockers, Jeff Delaune, Gerik Kubiak, Havard Grip, Gene Merewether, Russell Smith, Larry Matthies

JOSHUA VANDER HOOK | pg 46

Principal Investigator,
Autonomous Swarms of High-Speed Vessels

Joshua Vander Hook is an Autonomous Systems Researcher in the Maritime and Multi-Agent Autonomy group, where he provides expertise in optimization of multi-agent sensing, estimation, and path planning.

Pictured left to right: Viet Nguyen, Zaki Hasnain, Josh Vander Hook, Will Seto, Carlyn Ann-Lee; not pictured (past contributors): Dan Levine, Robert Freepartner, Amir Rahmani, Jean-Pierre de la Croix, Oscar Yang, Siddharth Krishnamoorthy

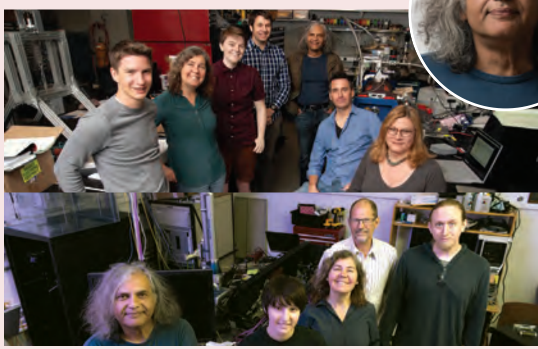
CONTRIBUTORS PROFILES

GAUTAM VASISHT | pg 18

Principal Investigator, PARVI

Dr. Vasisht is a Research Scientist in the Astrophysics and Space Sciences Section. His work is often collaborative, as the following team list shows.

JPL: Gautam Vasisht, Christopher Matthews, Stephanie Leifer, Christopher Paine, Thomas Lockhart; NExSci: Charles Beichman; Caltech: David Hover, Jason Fucik, Tom Barlow, Dimitri Mawet; American Museum of Natural History/Columbia University: Rebecca Oppenheimer, Rose Gibson

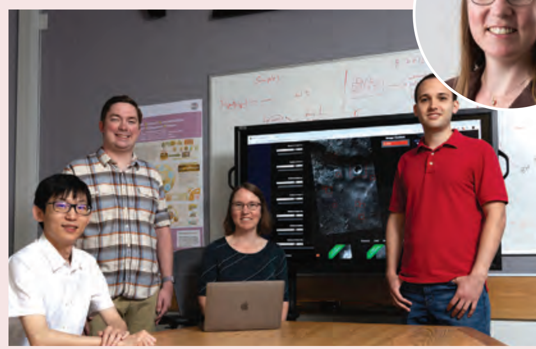


KIRI WAGSTAFF | pg 36

Principal Investigator, CNN for PDS

Dr. Wagstaff's research focuses on developing new machine learning and data analysis methods in support of science investigations. She is currently developing onboard science methods for the Europa Clipper mission and future Mars orbiters.

Pictured left to right: Steven Lu, Kevin Grimes, Kiri Wagstaff, Gary Doran; not pictured: Lukas Mandrake, Alice Stanboli, Jesse Cai, Jake Lee



JASON WILLIAMS | pg 50

Principal Investigator, CAL and Flight Instrument Lead

Dr. Williams performs research in the development of high-precision atomic clocks and quantum sensors for fundamental and applied science.

Jason Williams (PI for Atom Interferometry), Kamal Oudrhiri (Project Manager), Rob Thompson (Project Scientist), David Aveline (Ground Test Bed Lead), Ethan Elliott (Engineering Model Test Bed Lead), Chelsea Dutenhoffer (Mission Operations Systems Lead), James Kellogg (Launch Vehicle and ISS Integration Lead), James Kohel (Laser and Optical Subsystem Lead), Norman Lay (Communications Architectures & Research Section Manager), Robert Shotwell (Former CAL Project Manager), Nan Yu (Quantum Sciences and Technologies Group Supervisor)

The Office of the Chief Technologist would like to thank the following people for their contributions to this publication:

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JPL: Jordan M. Sotudeh—Content Lead, Writer and Editor, Chuck Manning—Consultant, and the Communications and Education Directorate.

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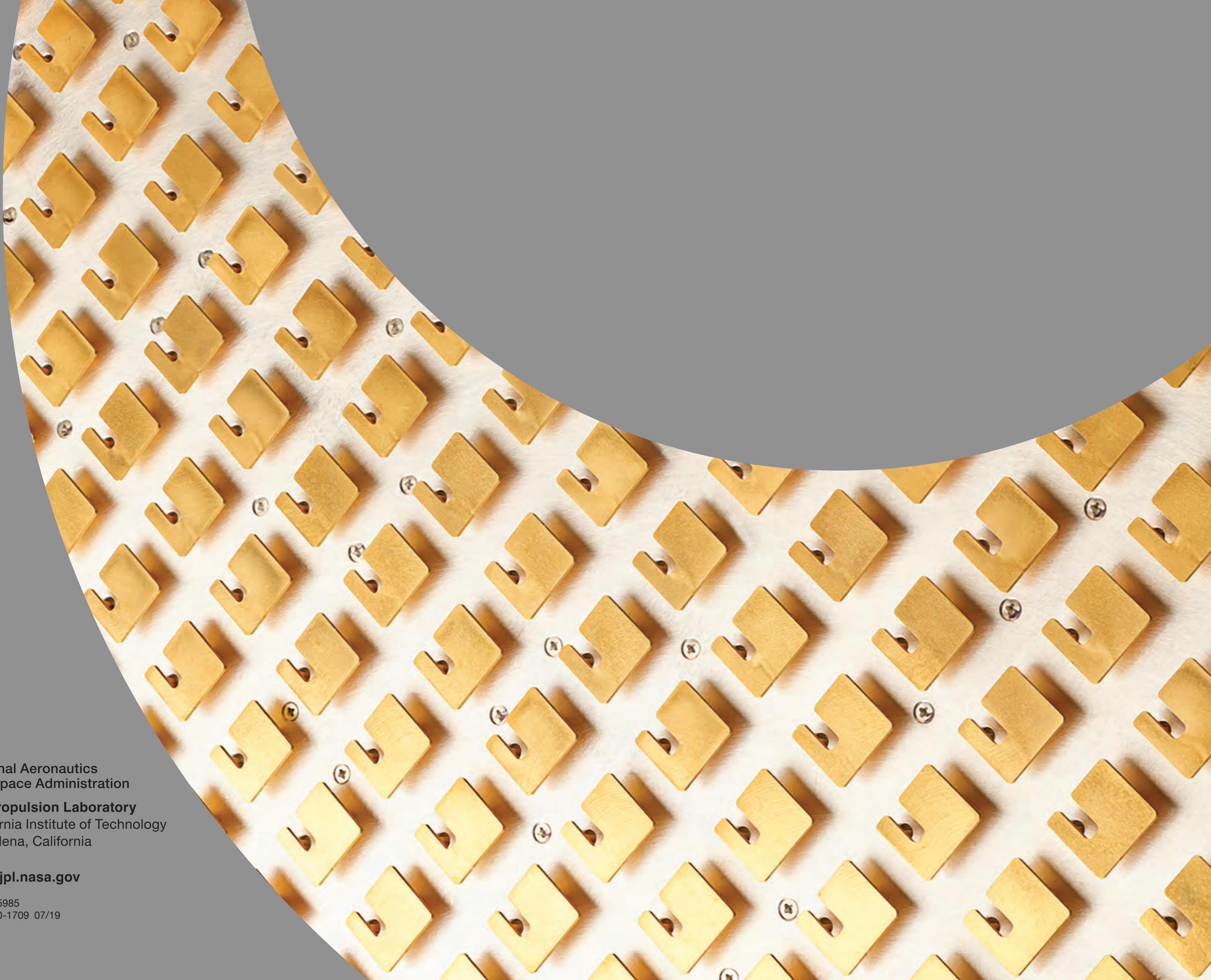

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