



National Aeronautics and  
Space Administration



2018  
**TECHNOLOGY HIGHLIGHTS**  
JET PROPULSION LABORATORY



About the cover: A candidate design for the Mars2020 parachute is shown in the process of inflating during a subsonic test at the National Full-Scale Aerodynamics Complex at NASA Ames. The parachute shown would survive an inflation load of nearly 91,000 lbf in this subsonic test. The design would later be tested as part of the ASPIRE risk-reduction effort and survive an inflation at Mach 2 and a peak load of 56,000 lbf, the highest load ever survived by a supersonic parachute. See page 48.

## OFFICE OF THE JPL DIRECTOR

JPL serves the nation by exploring space in the pursuit of discoveries that benefit humanity, and we remain proud of our mission as NASA's leading center for robotic exploration. Our spacecraft have a rich history of helping humankind expand its frontiers of knowledge, and we continue to work passionately to broaden those successes. During this past year alone we have renewed investigations of how mass is redistributed among Earth's atmosphere, oceans, land and ice sheets; probed the rings and atmosphere of Saturn with Cassini's spectacular finale;

and uncovered even more earth-like planets in our own Milky Way galaxy. All of these exciting discoveries have been enabled by the creative talent of JPLers, and their ability to conceive, develop, and operate innovative and challenging missions.

This creativity dates to our first mission in 1958, when Explorer 1 became the first satellite to be successfully launched by the United States. Since that milestone event, we have continued to develop and use technology to pursue our mission in innovative ways, ranging from using superconducting THz detectors to probe the early universe, and ultra-low temperature rechargeable lithium ion batteries to power rovers on the surface of Mars, to using long-lived ion thrusters to explore the previously unreachable worlds of Vesta and Ceres. The advancement of technologies for space remains a key part of JPL culture today.

In the pages that follow, you will find descriptions of technologies that are changing the way we envision future space exploration. For example, some JPLers are considering swarms of miniaturized robotic explorers that can

autonomously maintain a prescribed formation even while orbiting another world and reconfigure themselves as needed to optimize scientific return. Others are exploring how the latest techniques in additive manufacturing can be used to fabricate multifunctional structures and novel graded and microstructure alloys to revolutionize the way we design and build spacecraft. In an interesting mix of the old and the new, other JPLers envision building origami-folded structures that precisely unfurl as finely structured starshades that exquisitely block the light from distant stars in the search for dim exoplanets circling them. Still others investigate networks of smart sensors to measure our earth's physical, chemical, and biological processes, generating massive amounts of data from which our computer scientists can then glean meaningful information to help us better understand our home planet.

Welcome to this new edition of JPL Technology Highlights. I invite you to explore the breakthrough concepts described here, and encourage you to join us as we envision the future of space exploration in new ways.



**MIKE WATKINS**

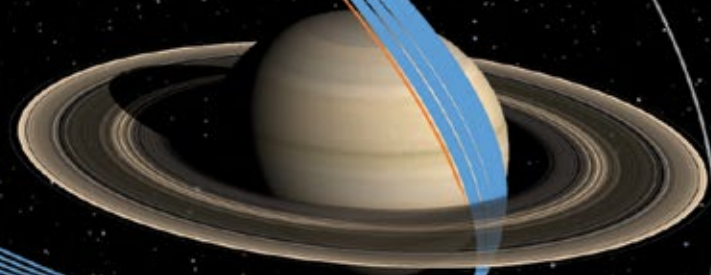
JPL Director

# CASSINI GRAND FINALE

After two decades in space, NASA's Cassini spacecraft ended its remarkable journey of exploration with a fiery plunge into Saturn's atmosphere. In April 2017, Cassini was placed on an impact course that unfolded over five months of daring dives—a series of 22 orbits that each passed between the planet and its rings. Called the Grand Finale, this final phase of the mission brought unparalleled observations of the planet and its rings from closer than ever before. Cassini represented a staggering achievement of human and technical complexity,

and returned images and measurements that vastly enhanced our knowledge and understanding of Saturn, while revealing new mysteries to be investigated by future missions.

Scientific and technological innovation is fundamental to the success of missions such as Cassini. The Office of the Chief Technologist provides for the development of innovative and strategic technologies at JPL that are essential for the success of future missions of exploration.



## OFFICE OF THE CHIEF TECHNOLOGIST

We live in an age of accelerating technological progress often driven by expanding markets for consumer products like smartphones, 3-D virtual reality simulations, and self-driving cars. The focus of advanced technology in our JPL community is on creating capabilities that enable exciting new robotic space missions. In some cases, commercially developed technologies can be utilized directly. Our challenge is to discern the capabilities offered by emerging technologies, to adapt or extend those that are applicable, and to develop those that are not available to meet the unique challenges of space exploration.

The following pages show that the technological opportunities at JPL have never been greater. For example, the innovations in the autonomous systems technologies seek to advance the science of autonomy by fusing technological advances in methodologies and computation with robotics. We can now envision space-based robotic swarms that autonomously transform their shape and function to accomplish a wide variety of engineering and scientific tasks.

Exciting progress continues to be made in the area of Additive Manufacturing, where a non-spherical, variable density Luneburg lens—a product that could not be manufactured by traditional subtractive means—can now be 3-D printed to fabricate a lightweight scanning antenna. In another novel development, recent advancements in Complementary Metal Oxide Semiconductor (CMOS) system-on-a-chip technology enable extreme miniaturization of digital spectrometers: a single CMOS chip can now incorporate the high-speed analog-to-digital converter, high speed spectral processor, and an integrated frequency synthesizer to provide 4000 channels with over 3 GHz bandwidth. Advances in nanotechnology have extended the frontiers of miniaturization even further. A molecular-sized Single Photon Detector is now the highest performing detector spanning the ultraviolet to mid-infrared range of the electromagnetic spectrum, where some of the most compelling science resides. At the other end of the scale, the Keck Cosmic Web Imager, installed in the

10-m Keck Observatory on Mauna Kea, utilizes a novel spectrograph that simultaneously records data at multiple wavelengths to probe the universe's dimmest objects. To better understand the workings of our home planet, JPL earth scientists have collaborated with NOAA to create a system for the near real-time delivery, visualization, and analysis of satellite data to enhance our knowledge of hurricane processes.

These examples represent just a small sample of the innovative technology work we do at JPL. With this 2018 edition of JPL Technology Highlights, I invite you to explore its pages further, joining us in our journey of discovery that embraces the opportunities that the future offers.

## FRED HADAEGH

JPL Chief Technologist



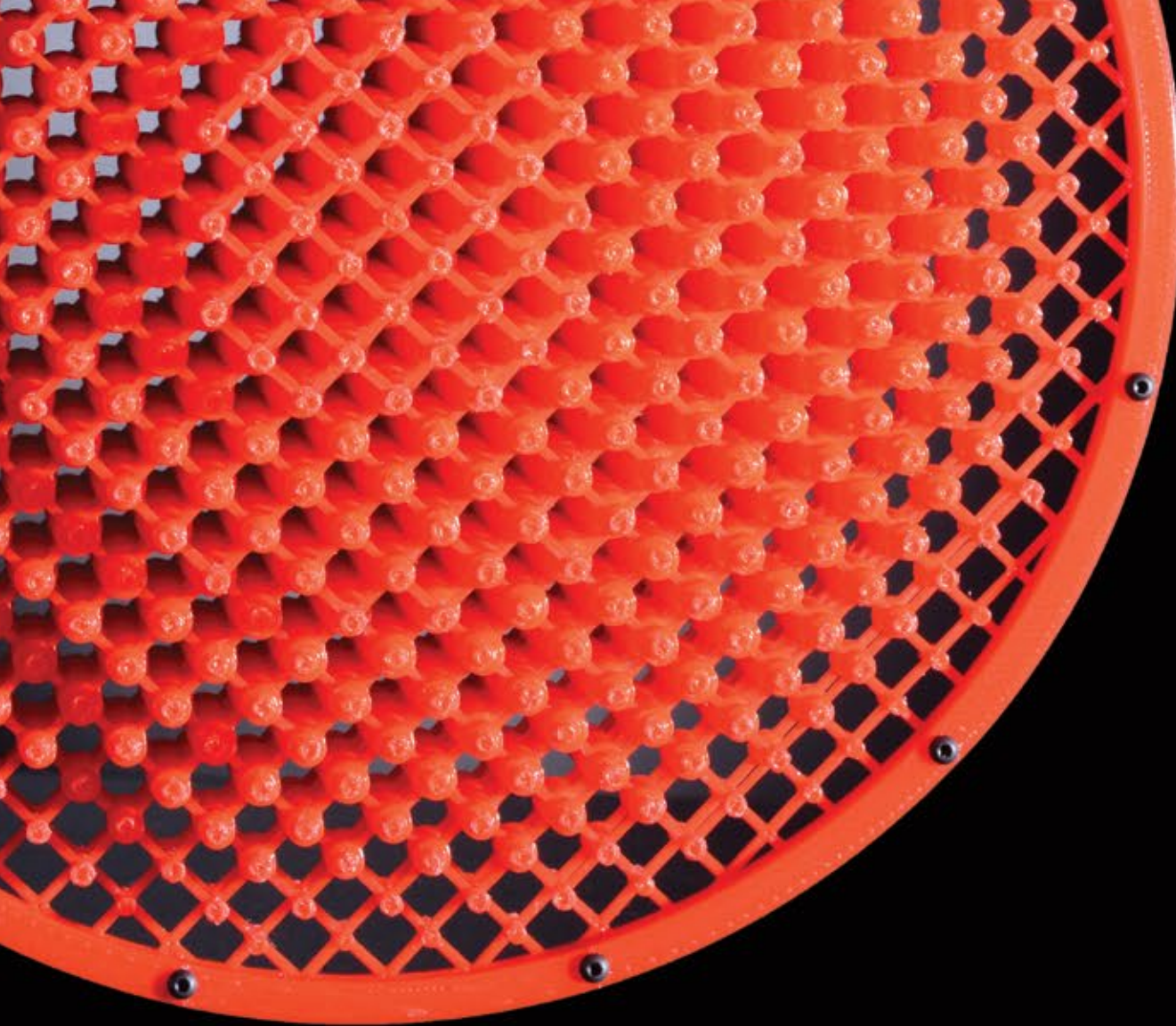
**HIGHLIGHTING THE MANY NEW  
AND IMPORTANT TECHNOLOGY  
IDEAS ESSENTIAL TO MISSIONS THAT  
ADVANCE OUR STATE OF KNOWLEDGE  
AND GREATLY CONTRIBUTE TO NASA'S  
EXPLORATION AND SCIENCE OBJECTIVES.**

[jpl.nasa.gov](http://jpl.nasa.gov) [scienceandtechnology.jpl.nasa.gov](http://scienceandtechnology.jpl.nasa.gov)

This JPL 2018 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.

**TECHNOLOGY HIGHLIGHTS**

TH:01	Printing Better Radar
TH:02	Shields Up!
TH:03	Tiny Rockets For Tiny Spacecraft
TH:04	PIXL Dust
TH:05	Portal To Distant Worlds
TH:06	Glassy Gears
TH:07	Happy Landings
TH:08	Eyes On The Storm
TH:09	Unraveling The Cosmic Web
TH:10	Configurable Computing
TH: 11	Looking For Life
TH: 12	Ice Pioneers
TH: 13	Radiation Relief
TH: 14	Mars Has MOXIE
TH: 15	Surviving Europa
TH: 16	Astro-Data Tools Aid Cancer Research
TH: 17	Sleuthing For Life
TH: 18	Big Power In A Small Package
TH: 19	Breathe Easy
TH: 20	Two For The Price Of One
TH: 21	Can You Hear Me Now?
TH: 22	Supersonic Chute
TH: 23	Tiny Tech, Huge Impact
TH: 24	Flying Swarms
TH: 25	CAST-ing For Success
TH: 26	Channeling Light
TH: 27	A Sideways Glance At Earth
TH: 28	Rappelling Other Worlds
TH: 29	Glimpses Of The Unseen
TH: 30	Dusty Skies
TH: 31	Bright Sourcing



TH/01

# PRINTING BETTER RADARS

New Earth-observing radar satellites will require multi-band, electronically scanned antennas to replace mechanically steered beams that are prone to wear and have limited lifespan. New 3-D printed radar antennas offer a robust, low-mass replacement.

Technologists are prototyping an innovative new approach to radar antennas created by additive manufacturing of complex non-spherical microwave “lenses.” New 3-D printing techniques can provide novel design options that are not possible via traditional manufacturing. For example, a Luneburg lens permits the power from a ring array of electronic transmit/receive modules to be focused and directed, creating an electronically scanned beam. The resulting antennas are inexpensive to make and can provide rapid beam scanning with no moving parts, which results in lower mass, higher reliability and a longer lifespan when compared to traditional rotating scatterometers.

A traditional Luneburg Lens has large bandwidth and excellent beam scanning capability. However, these lenses have not been previously utilized due to the fact that it is extremely challenging to fabricate a lens that is denser in the middle using traditional methods. Additive manufacturing via 3-D printing provides, for the first time, a practical and low cost method to fabricate a low-mass evolution of the Luneburg Lens.

JPL partnered with researchers at UCLA to develop a new lens design algorithm that uses a special ray tracing technique in conjunction with a novel synthesis method known as Particle Swarm Optimization, which searches for low mass solutions the way a swarm of

bees search for pollen by working in parallel. This technique has resulted in unique new lens designs that provide robust beam scanning and are thinner and lighter than a traditional Luneburg Lens.

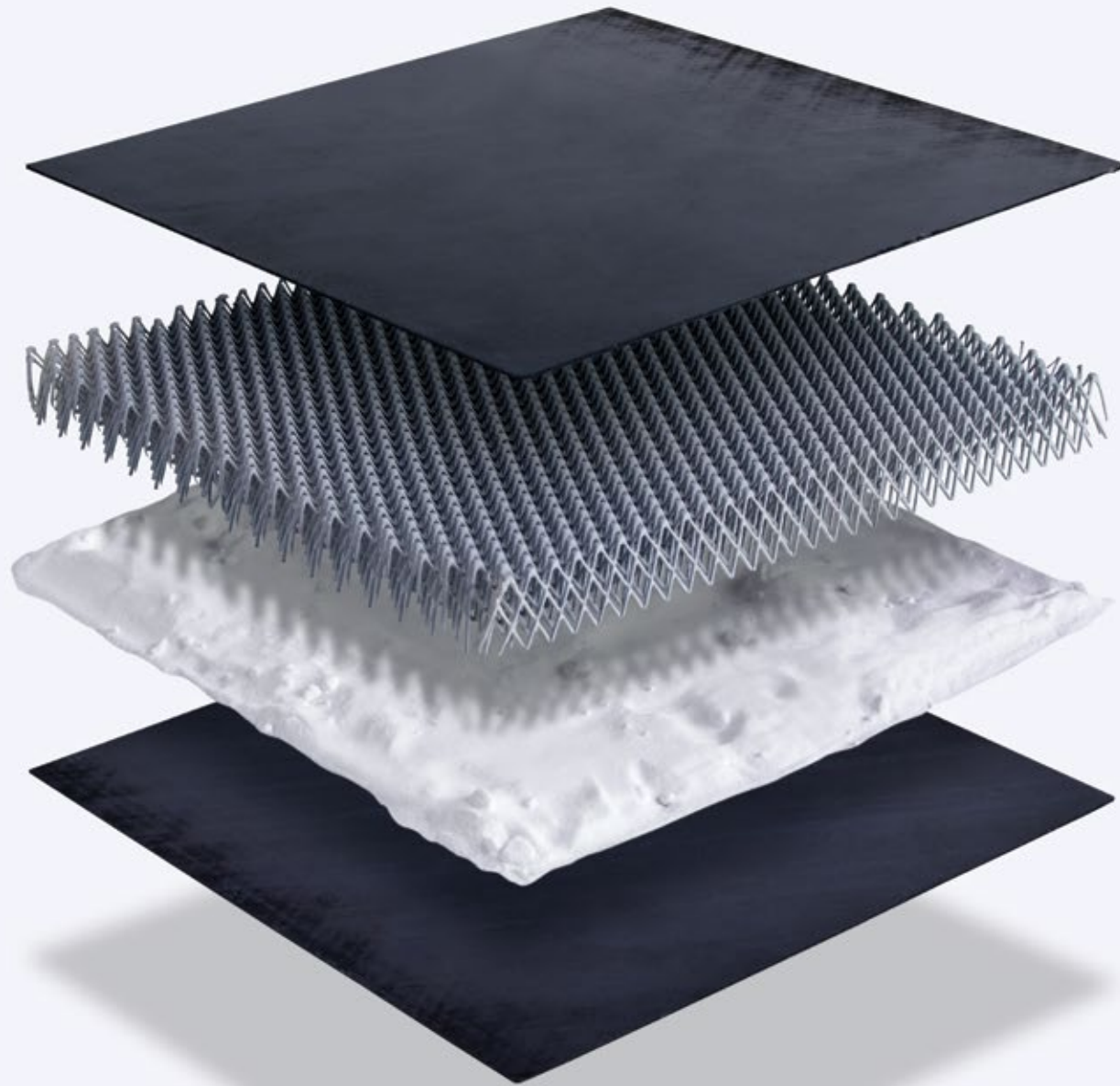
Engineers printed lenses out of a space-qualified polymer called Ultem. To further reduce mass, they developed the capability to 3-D print materials with infused metallic masses that create an artificial dielectric based on a 3-D printed lattice structure with variable-sized metal rings. The result is a design with lower mass than any previous lens antenna with comparable capabilities. In the future, it may be possible to print a multi-plane collapsible antenna that can launch flattened, then deploy to an operational configuration once in orbit.

**A NOVEL APPLICATION OF  
ADDITIVE MANUFACTURING  
RESULTS IN NEXT-  
GENERATION, COMPLEX  
MICROWAVE LENS  
ANTENNAS THAT CAN  
PROVIDE BEAM SCANNING  
WITHOUT MOVING PARTS**



TH/02

# SHIELDS UP!



Spacecraft traveling beyond Low Earth Orbit experience some of the harshest conditions known, including long exposure to the severe radiation experienced in deep space. New, multifunctional shielding designs may help to mediate this threat.

Once a spacecraft has left the protective embrace of the Earth's magnetosphere, hard radiation can wreak havoc with both electronics and human tissue over time. There is not only solar radiation to contend with, but micrometeorites, orbital debris and Galactic Cosmic Rays, or GCRs, that are particularly difficult to mediate. While many materials and techniques have been studied, the accepted practice has been to use aluminum hulls, and some specialized shielding around delicate electronics. But what if a shield could be designed that not only protected delicate electronics and humans from the ravages of radiation, but also contributed to spacecraft functionality?

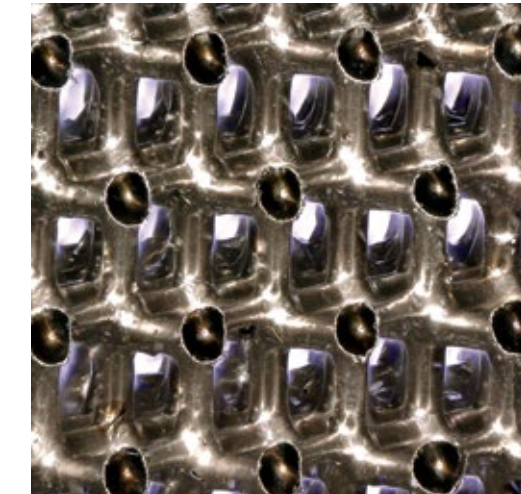
This was the genesis of a project to design more efficient radiation shields. Engineers have developed and tested panels made from two thin carbon fiber composite sheets that sandwich 3-D-printed hollow metal coated structures. The resulting sheets have open space inside, which is filled with a powder such as lithium hydride. This hydrogen-rich powder provides protection

from GCRs, which consist primarily of high-energy ionized protons, against which hydrogen is an effective shield.

However, the real beauty of this project is the multifunctional aspect of these panels — because these structures are 3-D printed, other useful mission functionalities can be engineered into them. These include tubing that provides space for wires in power distribution, sensors, antennas and even fluid transfer pipes for heat exchangers. This ability to utilize shielding mass as a functional part of the spacecraft could be a game-changer in spacecraft design. The panels are also stronger than trusses of similar mass, offering structural advantages as well.

Micrometeorite impact simulation tests using high-velocity projectiles have shown good stopping power within the panel, and the structures being investigated are easily deployed and interlocked in orbit. Next steps in development would include in-flight deployment for both radiation mitigation testing and multifunctional effectiveness.

**RADIATION IN SPACE IS A SERIOUS THREAT TO BOTH ROBOTIC AND CREWED SPACECRAFT. NEW SHIELDING DESIGNS ENABLE THE NECESSARY PROTECTION OF EQUIPMENT AND HUMAN PASSENGERS**



These nickel-plated panel trusses were printed using 3-D stereolithography. They can be designed to contain hydrogen-rich materials for radiation shielding or as tubes for heat exchangers or for sensor cabling.

TH/03

# TINY ROCKETS FOR TINY SPACECRAFT

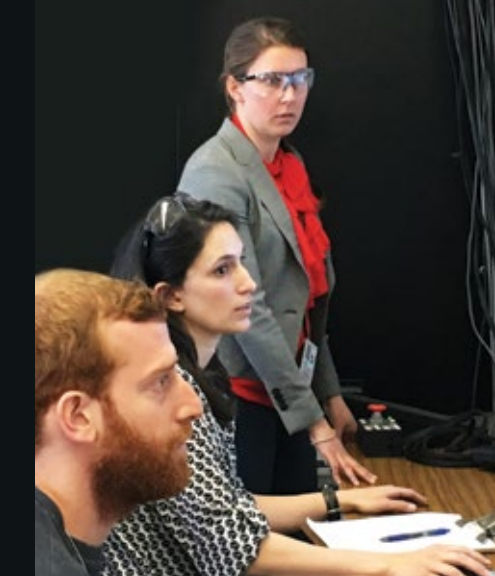
One of the challenges for ever-smaller spacecraft has been the means to maneuver them. New technologies are showing great promise for smaller high-performance hybrid rocket motors to propel small spacecraft.

Traditionally, rocket designers have had a choice between liquid propellants or solid fuels. Liquid-fueled rockets are complex, and the fuels can be difficult to store long term. Solid rockets are reliable and provide massive thrust for their size, but once ignited, burn furiously until their fuel is depleted, and cannot be reignited—they are generally a one-use system. While electronics have led the way in miniaturization, re-usable rocket engines are largely mechanical devices, and are much harder to shrink to fit into small packages. Researchers have developed a hybrid propulsion system—incorporating the benefits of both designs—to propel small spacecraft in the future.

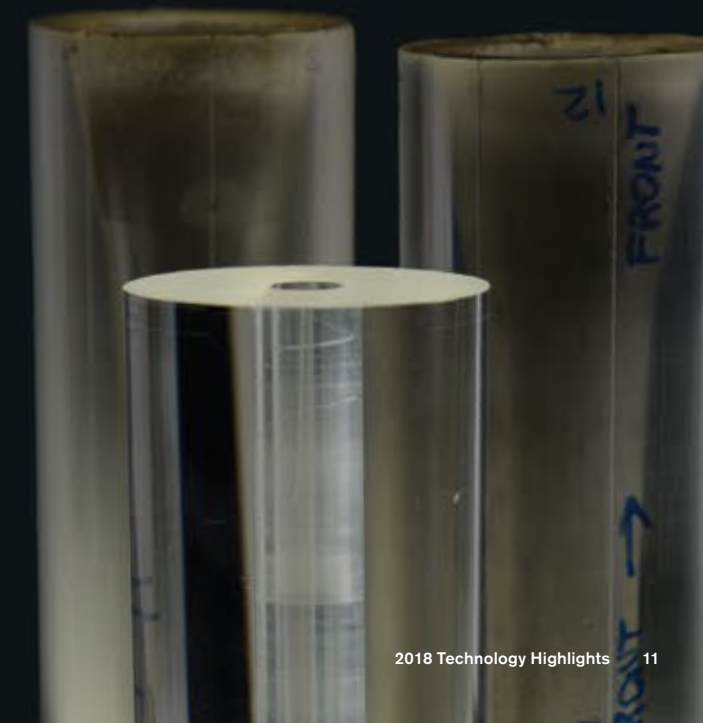
A hybrid rocket motor typically uses solid fuel and liquid or gaseous oxidizer. In this design, combustion can only occur when the oxidizer is introduced into the rocket motor, which makes the combustion more controllable and the motor safer. Additionally, many available hybrid propellants are non-toxic, further enhancing their safety, and require only about half of the plumbing of a liquid-fueled engine. The challenge has been to miniaturize these motors for compatibility with small spacecraft.

Acrylic fuel with gaseous oxygen is currently being tested for use as fuel in a small hybrid rocket motor. This combination is desirable because the diffusion-limited heat transfer in the motor limits the thrust level that can be achieved—important for controllability of small, low mass spacecraft. The gaseous oxidizer, while less dense than liquid oxidizers, simplifies the feed system and provides high performance. Such hybrid motors can be started, stopped, and re-fired multiple times without fuel storage issues. The available propellants allow them to be tolerant of much broader ranges of temperatures than most liquid bipropellant rockets, and thus more broadly applicable to space missions. This hybrid rocket motor should prove ideal for a number of scenarios, including CubeSats and small interplanetary spacecraft that require compact, high performance propulsion systems.

**HYBRID ROCKET PROPULSION SYSTEMS ARE LESS COMPLEX THAN TRADITIONAL LIQUID-BIPROPELLANT ROCKETS, WHILE ENJOYING SIMILAR PERFORMANCE, INCREASED SAFETY, AND THE ABILITY TO SURVIVE A WIDER RANGE OF TEMPERATURES**



Above: Ashley Karp (center) with Elizabeth Jens and Jason Rabinovitch monitor a successful test from control room. Below: unburned and burned PMMA fuel grain rods.





TH/04

# PIXL DUST

X-ray fluorescence spectroscopy and optical microscopy have both proved to be invaluable tools for exploring the surface of Mars. PIXL combines these two techniques into one compact package that provides visual context for the X-ray composition measurements.

To assess past habitability and the potential for biosignature preservation, and seek evidence of past life, it is vital to measure geochemical variations among grain-sized geologic features on the Martian surface. This type of science will provide key insights to conditions and processes across Mars' geologic history time and reveal chemical clues at scales critical for astrobiological investigations.

The Planetary Instrument for X-ray Lithochemistry (PIXL) is a microfocus X-ray fluorescence instrument that will be carried aboard the Mars 2020 rover. It measures the amounts and distributions of elements in tiny geological samples by focusing X-rays on a target and analyzing the fluorescence. Moving the beam across the sample reveals chemical variations in relation to visible features

imaged by PIXL's microscopic camera. PIXL will be capable of producing powerful science data from rapid line scans or spot analyses of the key rock components in seconds to minutes, to detailed hyperspectral elemental maps and highly sensitive trace-element measurements of individual grains, layers, cements, and coatings of soil grains. The detailed elemental maps obtained can contain up to thousands of 150-micron diameter points, and is capable of distinguishing differences between the compositions of a grain or vein from the surrounding rock. Correlated with the optical images, this will yield clear, comprehensive information without the ambiguities of bulk sample analysis that averages composition over a large sample.



PIXL Instrument engineering model in test

**SEEKING CLUES OF PAST LIFE ON MARS IS AN ENORMOUS UNDERTAKING. A NEW INSTRUMENT, PIXL, SCHEDULED TO BE FLOWN ON THE MARS 2020 MISSION, WILL EXAMINE SAND-GRAIN SIZE SAMPLES FOR SIGNS OF LIFE, PAST OR PRESENT**



TH/05

# PORTAL TO DISTANT WORLDS

Solar System Treks are like an extension of Google Earth into the solar system. Rocky worlds have been mapped and imaged by spacecraft since the 1960s, but these data sets have never before been combined into an interactive virtual environment.

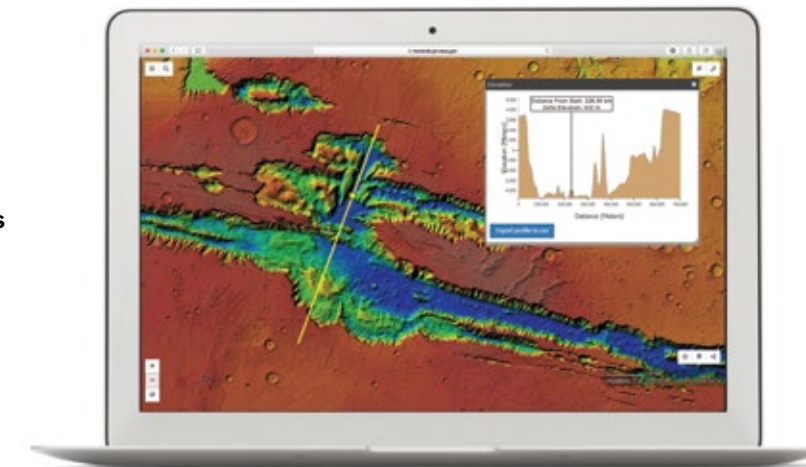
JPL's Solar System Treks feature high-resolution, global representations of the moon, Mars, Vesta and Ceres created from extensive imaging and measurements. This new portal offers a truly global view, with the ability to do ground-level analyses and data-layer comparisons on any mapped body. Such data visualization plays a vital role in mission planning, planetary science, education and public outreach.

These user-friendly, online portals integrate a suite of interactive tools that feature thousands of georeferenced data sets that can be stacked, blended, and combined in ways that reveal information beyond what is seen in individual layers. Users can perform a wide range of detailed engineering and scientific analyses, and data can be viewed as two-dimensional maps or on three-dimensional spinnable, zoomable globes. Visualizations are enhanced by sophisticated analytic tools including distance and elevation profiles, ray-traced surface lighting,

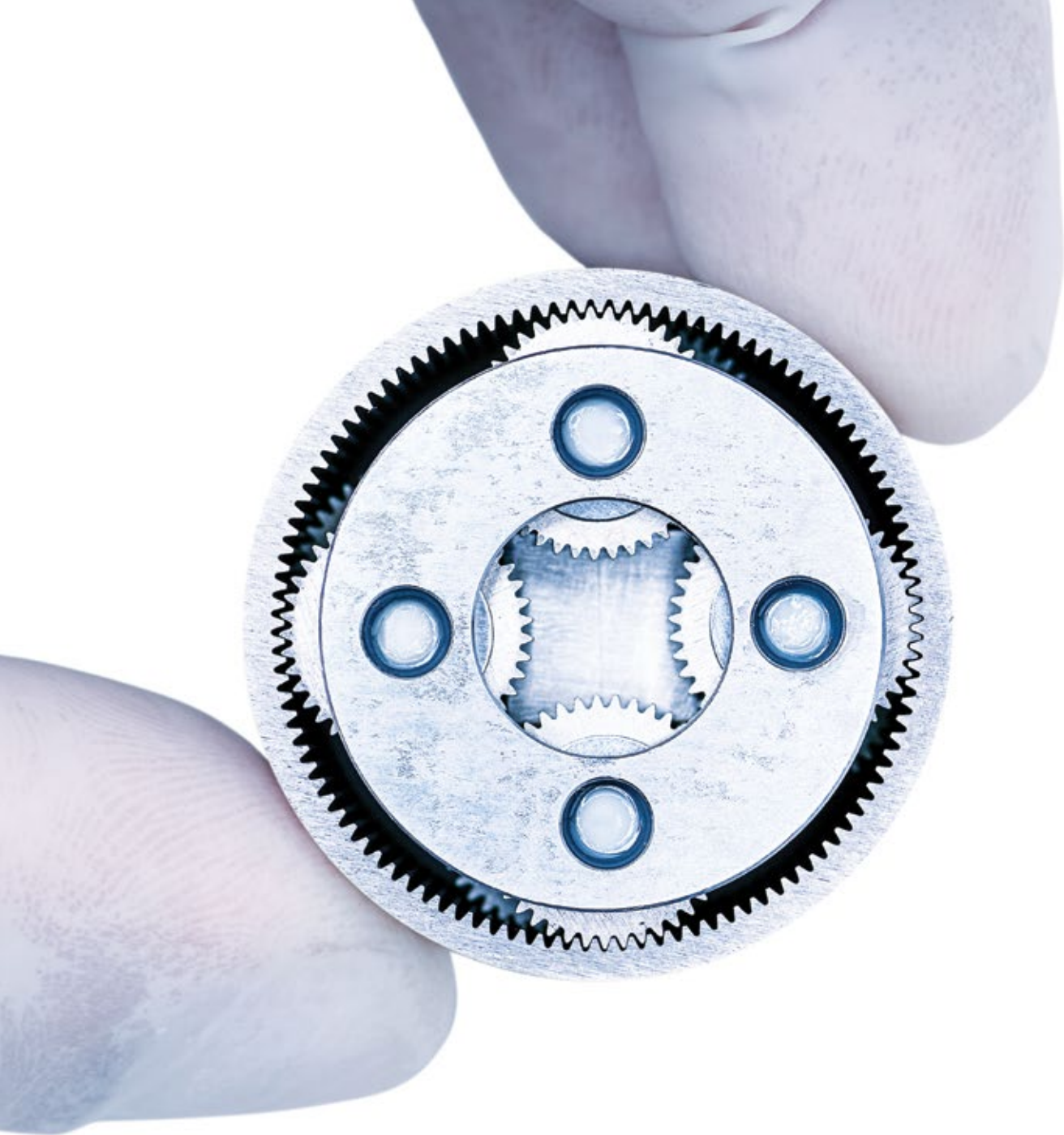
machine-learning-based boulder and crater detection, and slope analysis. Users also have the ability to select any surface feature or region of interest, then download an STL or OBJ file for 3-D printers, allowing them to create scale planetary surface models in three dimensions.

Powerful software design on the server side minimizes requirements on the user side with no need for additional client software. Solar System Treks provides an excellent platform for sharing researchers' modeling and simulation algorithms, which then become widely accessible online analysis tools for the research community. It also provides an engaging interactive experience for the public at large to explore these worlds. Solar System Treks are being used by NASA and international partners to support current and future missions, both robotic and human. Upcoming portals featuring Phobos, Ceres, Titan, and several of Saturn's icy moons are currently under development.

**NEW INTERACTIVE MAPS INCLUDING FULL SETS OF ANALYTICAL TOOLS, ARE NOW AVAILABLE FOR SCIENTIFIC RESEARCH AND FOR THE PUBLIC TO VIRTUALLY EXPLORE THE SOLAR SYSTEM**



An elevation tool measures a cross section of Mars Valles Marineris in Solar System Treks Interactive portal.



TH/06

# GLASSY GEARS

Spacecraft that use gearboxes to facilitate instrument function must heat the lubricants to keep them fluid, robbing the spacecraft of power. Gear trains using Bulk Metallic Glass alloys do not require lubrication and are ideal for future missions to cold, icy worlds.

Bulk Metallic Glass (BMG) components do not require wet lubricants, are tougher than ceramics, twice as strong as steel, and offer better elastic properties than either material. They do not become brittle in extreme cold, and will be ideal for exploring icy moons.

Metals generally have an organized, crystalline arrangement. But if you heat them up they melt to form a liquid, and the atoms become randomized. Cool them rapidly enough, about 1,832 degrees Fahrenheit (1,000 degrees Celsius) per second, and their non-crystalline, "liquid" form can be captured in the solid form. The random arrangement of atoms in this form is said to have an amorphous or non-crystalline microstructure. This gives these materials their common names of "amorphous metals," or "metallic glasses." BMGs can be injection-molded like plastic using

commercial machines, allowing for incredible complexity and low-cost in cast parts.

A range of activities including rover mobility, the pointing of antennas, and the drilling and acquisition of samples utilize gearboxes. In environments where the temperature drops below about -60 degrees Fahrenheit (-50°C), current gearboxes require heating to keep the lubricants fluid — the Curiosity rover, for example, must heat lubricants in moving parts before activities are initiated. Electric heaters that are used to do this drain power resources — power that could otherwise be used for powering instruments for productive science investigations.

These new materials eliminate the need for heaters, reduce system complexity, and preserve power for instrumentation to increase science

return. BMGs offer greater wear and corrosion resistance, and are less expensive to fabricate than their traditional metal counterparts.

Engineers have developed a 3-stage planetary gearbox assembled from injection-molded components made from BMG alloy. These gearboxes are being life and performance tested, unheated, at temperatures as low as minus 323 degrees Fahrenheit (-200°C), and are ideal for use in cold environments such as Europa, Enceladus and other icy moons.

**NEW MATERIALS CALLED BULK METALLIC GLASS (BMG) ALLOY ARE TOUGHER THAN CERAMICS, TWICE AS STRONG AS STEEL, AND ARE IDEAL FOR MOVABLE STRUCTURES ON SPACECRAFT BECAUSE THEY REQUIRE NO WET LUBRICANTS**





TH/07

# HAPPY LANDINGS

When a lander reaches Mars, it has only minutes to maneuver and land. New guidance systems should enable safer landings on Mars, and permit access to scientifically compelling regions that were previously considered too rugged for safe landing.

Since 1976, only seven spacecraft have successfully landed on Mars. In each case, the landing zone, called a landing ellipse, has gotten smaller and the landing more accurate. Spacecraft arrive there like a rifle bullet, plunging directly into the atmosphere, and have about seven minutes to pinpoint their touchdown zone. This is done with a combination of inertial guidance, based on bearings taken shortly before the lander enters the atmosphere, and augmented by real-time radar readings of the surface. But the string of successful landings has been limited to flat terrain. To get close to specific targets in complex terrain requires more accuracy and onboard navigation ability.

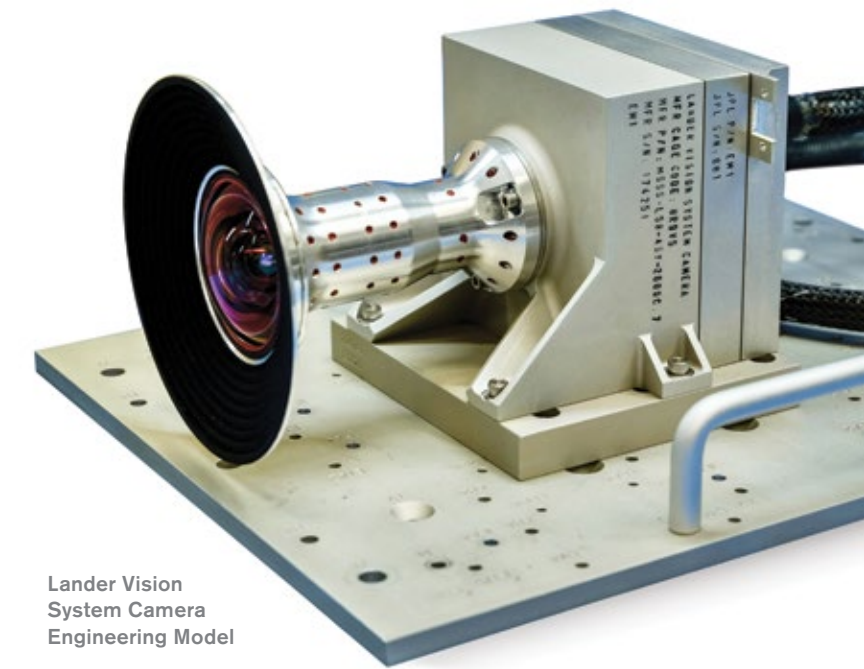
The application of Terrain Relative Navigation reduces the uncertainty in position from miles down to a few tens of yards. This new capability will guide future spacecraft during the Entry, Descent and Landing (EDL) phase using visual cues to determine its location relative to the desired landing zone. Visual data from a down-

ward-facing camera is compared to an onboard map of the Martian surface. Matched terrain features are then used to determine position in a map.

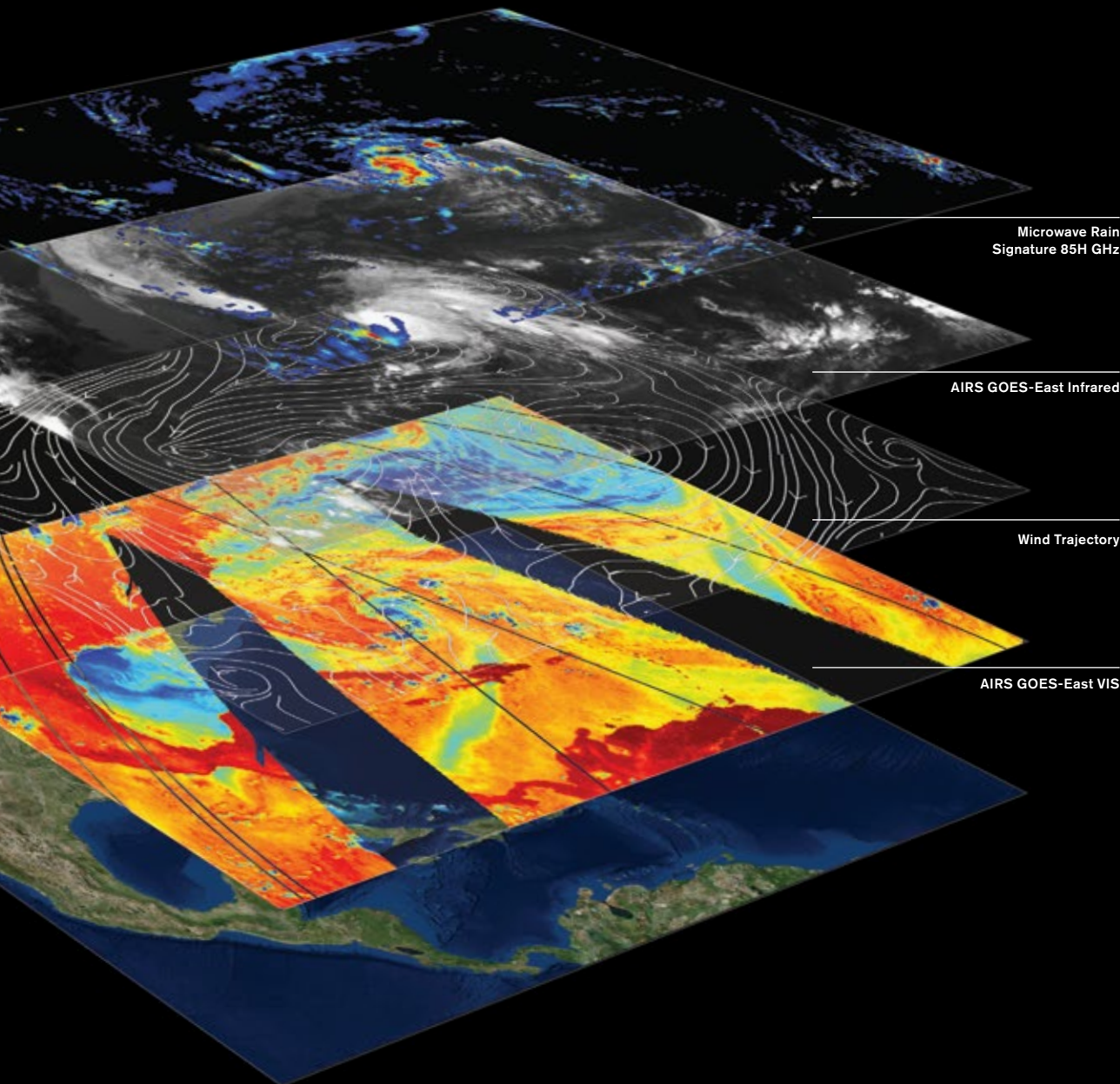
Once the lander is low enough to begin rocket-powered descent, a safe target selection algorithm uses this accurate position to select a nearby safe location in the ellipse to target. With active correction of the trajectory during flight, landers can now be sent to more precisely targeted locations on Mars. Due to this ability to actively avoid hazards, landers can be guided to sites once deemed inaccessible. Previous missions were sent to relatively safe areas with large, flat expanses that allowed for a moderate amount of navigational error. With TRN, landing ellipses can include steep slopes, craters, boulders, scarps and other terrain that, while potentially hazardous, promise great scientific rewards.

While TRN has been successfully implemented in drones and military cruise missiles on Earth, Mars 2020 will be the first fully autonomous use of TRN in spaceflight.

FROM ATMOSPHERIC ENTRY TO TOUCHDOWN, MARS 2020 WILL HAVE ONLY ABOUT SEVEN MINUTES TO DETERMINE A SAFE LANDING SPOT. NEW SYSTEMS WILL ENABLE A SAFER LANDING IN EXCITING TERRAIN



Lander Vision System Camera Engineering Model



TH/08

# EYES ON THE STORM

To understand the evolution of hurricanes, it is critical to leverage a diverse set of measurements and sources. A new interactive portal is addressing this need with enhanced merging of available data for improved analysis, modeling and prediction of these destructive tropical storms.

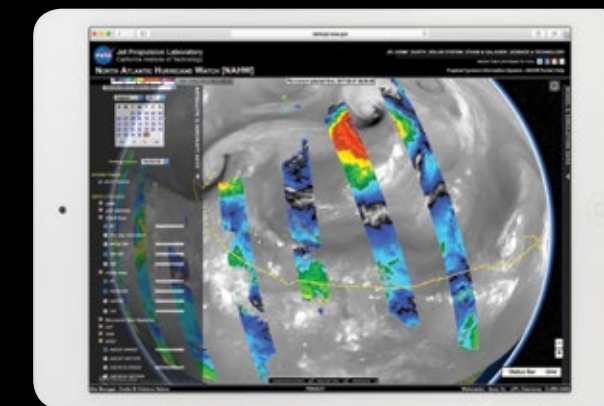
Hurricanes have a vast societal and economic impact, with costs in the billions. Many lives are lost, so better prediction is critical to forewarn endangered populations. However, despite the enormous amount of predictive data available from satellites and other sources, the integration of this information is incomplete, leading to lost opportunities in more precise prediction and avoidance of the most severe outcomes.

JPL has worked in coordination with NOAA to create a web-based portal called the North Atlantic Hurricane Watch, or NAHW, for near real-time delivery, visualization and analysis of satellite data and model forecasts that enhance our understanding of hurricane processes. This system covers the North Atlantic and, more recently, the East Pacific region. The evolution of tropical storms depends on a variety of meteorological conditions including wind speed and direction, moisture content profiles, air and water temperatures, and

much more. This portal provides fully interactive visualization and online analysis tools to collectively utilize all available data to investigate and predict how tropical storms form, intensify and propagate.

The data integration provided by the NAHW portal is a significant step forward in revealing the complex processes that lead to hurricane genesis and evolution. Another unique feature of this portal is its integration with software simulators that can translate model output into the parameters observed by the satellites, allowing for direct comparison of models to observations to evaluate and improve them.

The NAHW portal was designed to facilitate interactive collaboration between engaged institutions and NOAA's observation and research database for an improved understanding of large-scale weather processes. Its utility was recently demonstrated by successfully predicting the intensification of



**A NEW INTERACTIVE PORTAL OFFERS GLOBAL ACCESS TO MULTIPLE INTEGRATED DATABASES AND TOOLSETS WHICH WILL REVOLUTIONIZE THE UNDERSTANDING AND PREDICTION OF HURRICANE DEVELOPMENT AND PROGRESSION**

2015's Hurricane Joaquin well ahead of other modeling methods.

NAHW provides a multi-agency, interactive and widely-available method of interrogating previously separate models and observations, combining a variety of data, all available within a common analysis system.

Opposite page: example of multiple layers of correlated data accessible through the NAHW interactive portal.



TH/09

# UNRAVELING THE COSMIC WEB

High atop a rocky, volcanic peak on the island of Hawaii, astronomers are probing the previously unexamined spectra of incredibly distant, difficult to observe objects. This new instrument, developed by JPL and Caltech, is called the Keck Cosmic Web Imager (KCWI) and is installed at the Keck Observatory in Mauna Kea, Hawaii.

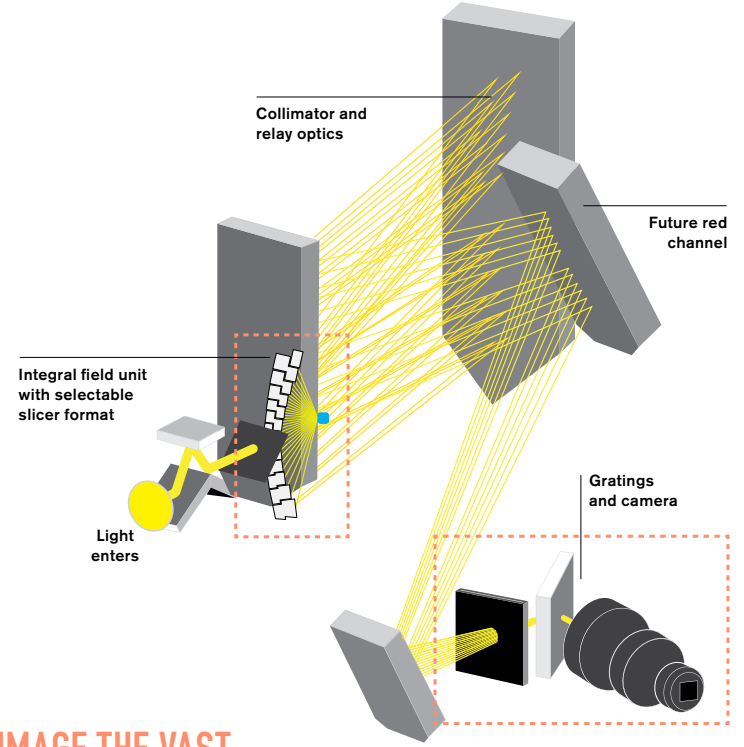
Classical spectrographs utilize a single slit to select light from the telescope focal plane and require many stepped observations to measure an extended object. This is a time-consuming process. The KCWI utilizes a novel optical system called image slicer technology. In a single observation, it simultaneously records an image of the object at multiple wavelengths, allowing the creation of both images and spectra.

In addition, the spectral resolution is adjustable, enabling the instrument to be customized for a wide range of observations, including the study of extraordinarily dim extended objects. Targets include black holes within star clusters and observation of the cosmic web—the diffuse streams of gas between galaxies that are millions of light years distant. The instrument can also detect the rotational velocities and relative motions within dim, distant objects. A unique capability is the near simultaneous sampling of the target

and sky background. This improves image contrast for measurements in which the background intensity is comparable to the brightness of the target.

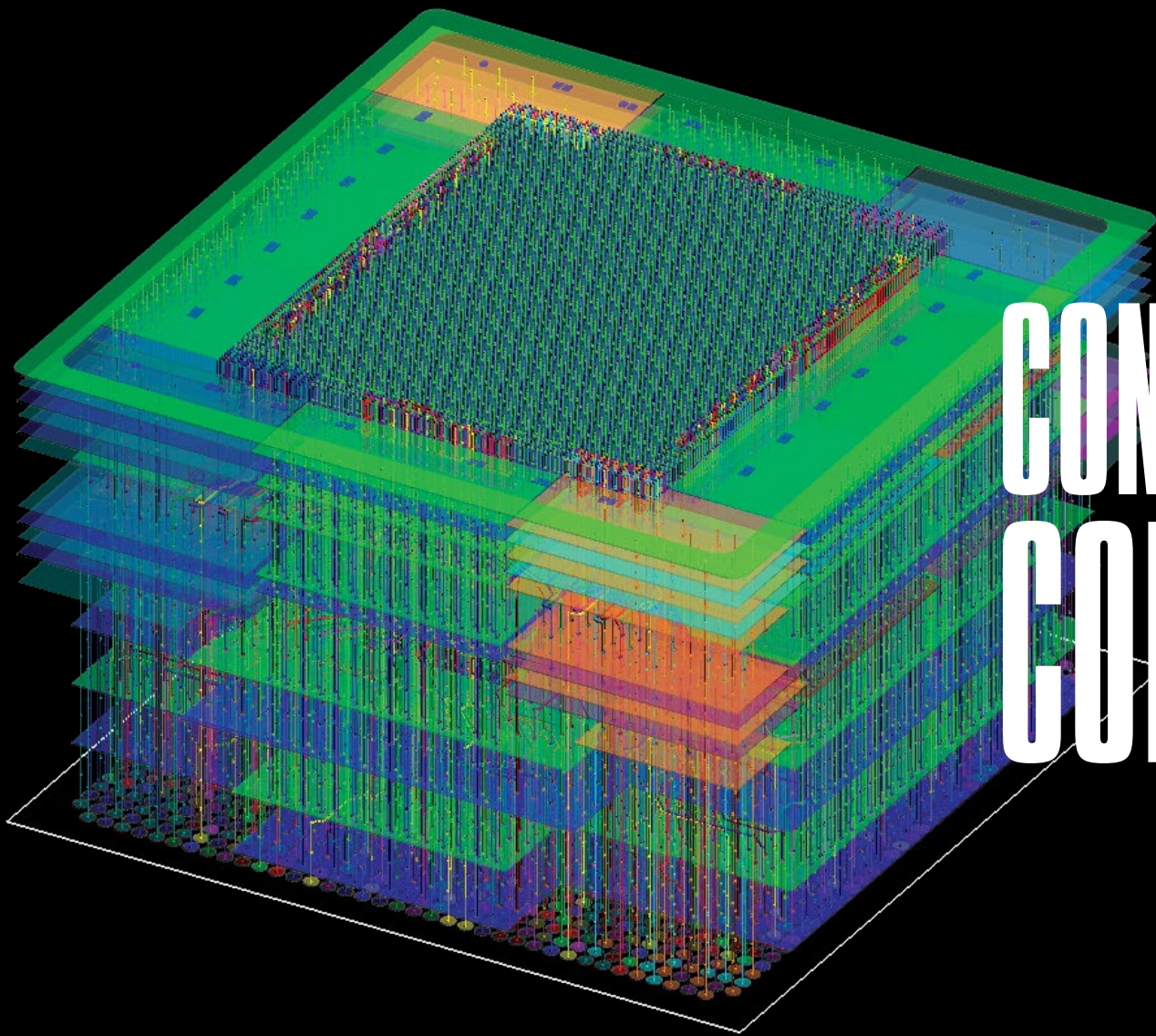
Early results in the shorter wavelengths indicate a sensitivity over twenty times that of its predecessors, and efforts at longer wavelengths are under way. The KCWI was designed and is operated in partnership with the University of California at Santa Cruz and the W. M. Keck Observatory.

**A NEW INSTRUMENT DESIGNED TO IMAGE THE VAST WEB OF GAS THAT CONNECTS GALAXIES ALLOWS ASTRONOMERS TO PEER INTO THE MOST REMOTE REACHES OF SPACE, PROVIDING A NEW LOOK AT SOME OF THE DIMMEST OBJECTS IN THE UNIVERSE**



Ray traced optical path through components of the Keck Cosmic Web Imager.

Opposite page: Hector Rodriguez, senior mechanical technician, works on the Keck Cosmic Web Imager in a clean room at Caltech. Credit: Caltech



TH/10

# CONFIGURABLE COMPUTING

The current generation of radiation-hardened processor chips are inadequate for future deep space missions, especially when autonomy is required. New “chiplet” designs represent a two orders-of-magnitude advance over processors currently in use.

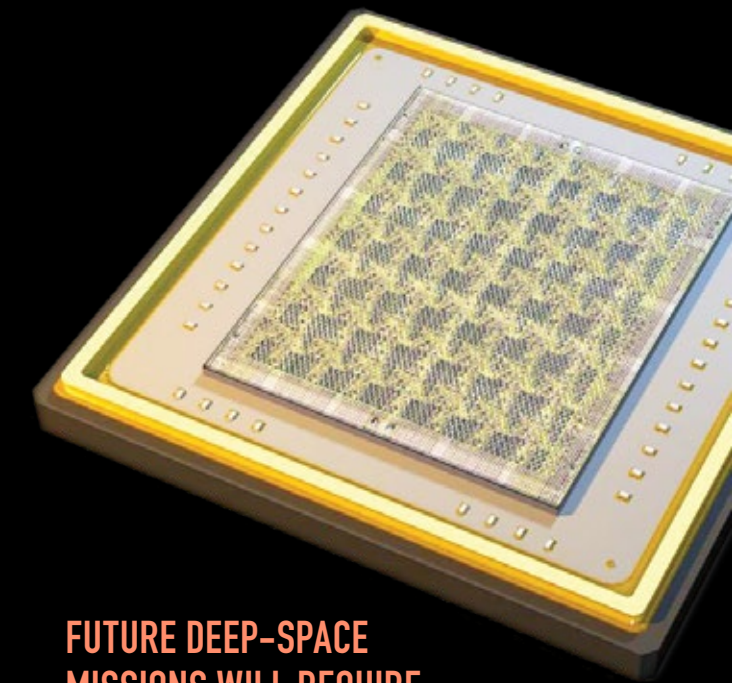
JPL is partnering with Boeing and the U.S. Air Force to develop a radically new concept that uses “chiplets” as the basis for a flexible computing architecture that will meet the needs of NASA missions through 2030 and beyond. This results in one hundred times the computational capability of current spacecraft processors while using the same amount of power. In addition, by dynamically setting its fault tolerance operating point, it provides an unprecedented ability to continually optimize performance to meet evolving mission needs.

Many of NASA's current and near future robotic spacecraft fly with microprocessors that are as much as two decades behind those available commercially. This is because many electronic components used in spacecraft must be hardened against radiation and the harsh conditions of space. In the past, such chips were developed primarily for military applications, are quite expensive, and are at least 20 years behind current commercial microprocessor performance.

Chiplets can be arranged in an almost endless variety of configurations that

can be customized for specific functions. Not only can they be optimized for overall mission objectives before launch, but can also be further reconfigured during flight as mission needs dictate. Chiplets utilize state-of-the-art processor circuitry—essentially the same type that is in your smartphone. Just as in your smartphone, power is optimized on an instruction-by-instruction basis, and just as in your phone, unused elements of a chiplet can be put to sleep or powered off completely. Unlike your phone, however, the standard commercial circuits are replaced with custom radiation-hardened, high reliability versions that can withstand not only extreme radiation, but also extreme temperatures.

This new processor architecture delivers the increased capacity and reliability that future missions will require along with a continuously variable operational flexibility never before available in a flight-rated computing system. The operation can be dynamically changed to meet the needs of specific mission phases or the situation of the moment. This is critical to autonomous functioning in the complex, unpredictable space environments of future missions.



**FUTURE DEEP-SPACE MISSIONS WILL REQUIRE A NEW GENERATION OF RADIATION AND TEMPERATURE TOLERANT COMPUTERS. FASTER MICROPROCESSORS WILL MEAN GREATLY ENHANCED CAPABILITIES FOR THE NEXT GENERATION OF ROBOTIC EXPLORERS**

Opposite page: digital Kyocera image of the planned HPSC Chiplet packaging.  
Credit: courtesy of Boeing and Kyocera

TH/11

# LOOKING FOR LIFE

When the first robotic landers make their way to the icy moons orbiting the planets of the outer solar system, microscopic imagers that can detect microorganisms at very low concentrations will be critical for the detection of life.

New microorganism detector systems have been developed for destinations including Europa, Enceladus, Titan, Ganymede, and Mars. The Digital Holographic Microscope, or DHM, provides unique capabilities for imaging extremely small organisms via the use of holographic techniques.

Using a compact laser and optics, DHM records a 3-D interferometric image of a tiny fluid sample that encodes both the phase and amplitude of the light. This information can be used to compute the image information at any position along the light path. In effect, this images the sample in three dimensions, allowing researchers on Earth to reconstruct the entire volume of the sample in depth, rather than a single plane like a conventional microscope. In essence, the DHM sends a 3-D representation of a tiny aquarium and the possible life-forms within. This data is compressed as a two-dimensional hologram, resulting in lower data rates and reliable image reconstruction.

There are additional benefits to this type of imaging. Because the technique also records the index of refraction of the object rather than just the absorption, transparent objects—such as many types of microbes—can be imaged without the need to stain them with dyes. The technique also allows researchers

to differentiate between mineral grains and organic materials. The holographic images can be captured at video frame rates, allowing the observation of sample dynamics. Researchers analyzing reconstructed data will be able to differentiate between inert objects and life forms almost instantaneously. The instrument also requires minimal sample preparation, and has no moving parts, both important for mechanical simplicity and reliability.

The DHM is, to date, the only compact device capable of imaging very low concentrations of microbes comparable in size to Earth bacteria. Planned enhancements include fluorescent imaging ability, which will provide additional information about the possible presence of proteins, lipids and nucleic acids in a sample—all possible indicators of life.

A fully functional DHM has been tested on Earth in environments ranging from Death Valley to Greenland with promising results. This work was accomplished in collaboration with Portland State University, with additional support from the Gordon and Betty Moore Foundation.

**SEARCHING FOR LIFE IN THE OUTER REACHES OF OUR SOLAR SYSTEM WILL BE ONE OF THE MOST IMPORTANT UNDERTAKINGS OF THIS CENTURY. A NEWLY DESIGNED 3-D HOLOGRAPHIC MICROSCOPE MAY PROVIDE OUR FIRST LOOK AT LIFE ON OTHER WORLDS**

Right: A compact version of the DHM instrument with inset image of a single *Euglena* captured from multiple video frames. The color reconstruction enables visualization of various features (eyespot, nucleus, etc.) over time as the organism rotates during swimming.





TH/12

# ICE PIONEERS

Using off-the-shelf components and custom 3-D printed parts, engineers are developing and testing inexpensive autonomous submersible robots to simulate the future navigation of sub-surface tunnels on icy moons.

Roboticists are exploring moulines on Earth, tunnels formed when sun-warmed surface water melts through hundreds of feet of ice to form a channel through a glacier. Researchers hope to learn how to navigate and map these twisting, complex and challenging channels to better understand how to do so on icy moons in the outer solar system.

The best way to explore them is with robotic submersibles. These robots are built with both off-the-shelf commercially available components and custom 3-D printed parts, allowing for rapid-prototyping and quick revisions as experience is gained. They are then lowered into the frigid channels and either allowed to sink via controllable buoyancy or maneuvered by small thrusters. The probes are tethered to a surface control unit from which they are manually navigated, and record detailed data as they traverse the ice tunnels. The goal is to develop new ways of navigating these complex passageways while mapping them with a compact LIDAR unit, which continually scans the surroundings. The data ultimately allows the researchers to construct a full-length, three-dimensional map of the moulin as

it twists and turns through the mass of the glacier. Video imagery captured by onboard cameras during the probe's descent allows the tunnel's visual features to be correlated with the LIDAR-generated models.

A JPL research team recently returned to Alaska to continue experiments with these inexpensive prototypes in Earthly glaciers, and their experience navigating these analogs of Jupiter and Saturn's moons will assist the designers of submersible probes in the future.



Probe being deployed in Alaskan glacier.



3-D rendering of a mapped ice tunnel.

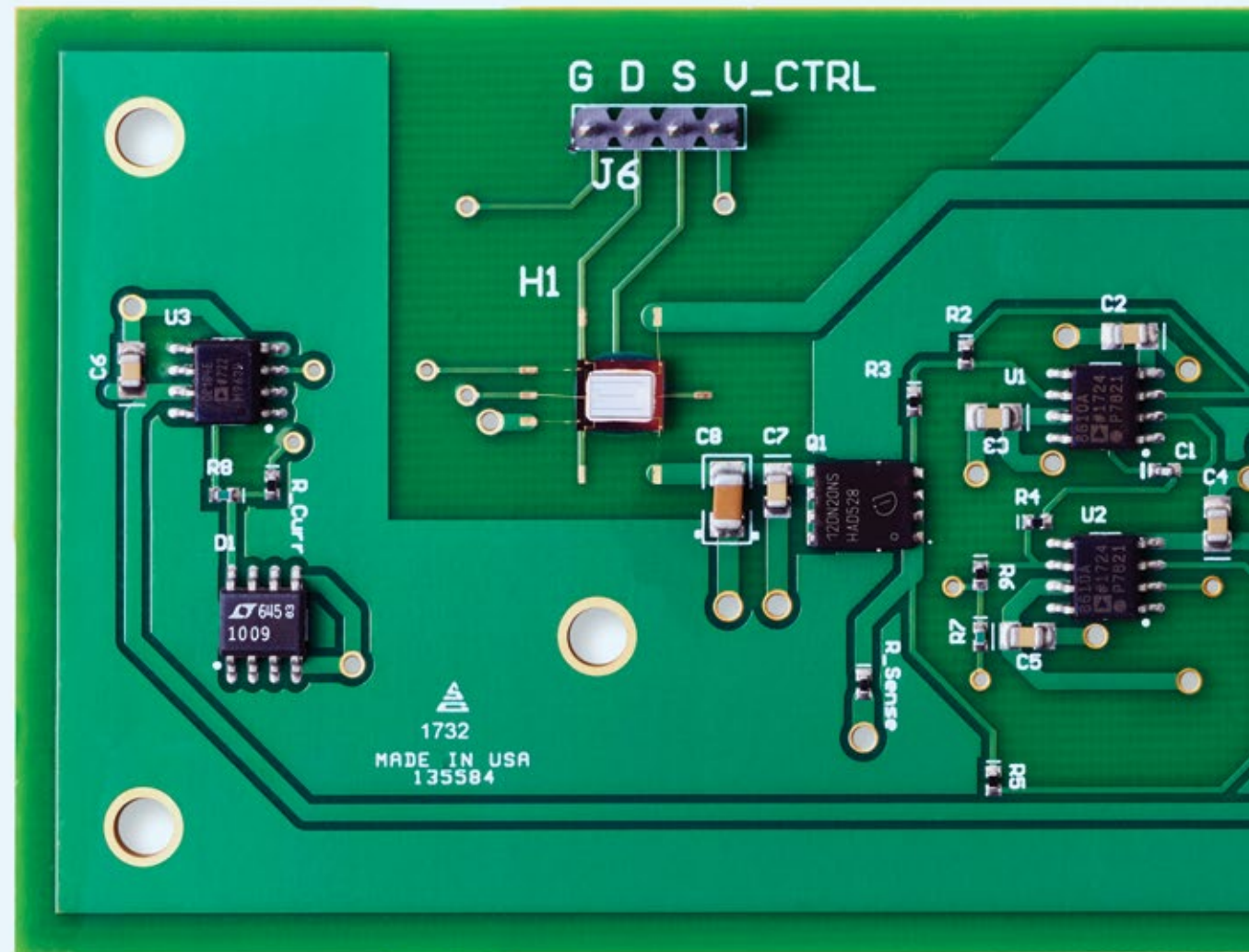
**RESEARCHERS ARE CONSTRUCTING SUBMERSIBLES THAT AUTONOMOUSLY PROBE UNDERWATER ICE CAVES ON EARTH WITH SCANNING LIDAR AND VISUAL IMAGERY TO PREPARE FOR THE EXPLORATION OF ICY MOONS SUCH AS EUROPA**

Opposite page: Laboratory testing of a prototype autonomous robotic submersible.



TH/13

# RADIATION RELIEF



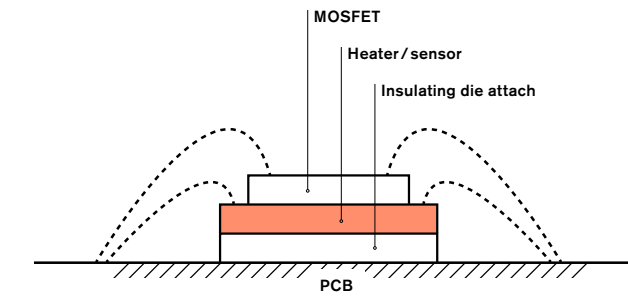
The outer solar system is a cold, radiation-bathed environment where spacecraft electronics are challenged to their limits. New technology can both protect electronics from cold and aid in recovery from radiation damage.

Traditional designs for probes that traverse such environments has involved encasing electronics in a thick metal vault, and heating the entire enclosure—a power-hungry approach. Spacecraft operating beyond low Earth orbit are also exposed to much higher levels of radiation, which can damage electronic components. Semiconductor devices can recover from radiation damage by controlled thermal annealing.

Localized heating at the component level can efficiently solve both challenges. Engineers have developed a way to use a network of tiny heaters and temperature sensors to reduce energy consumption by heating only specific components. Secondly, these heaters act like an electromechanical “antibiotic,”

targeting only radiation-damaged components and regenerating their performance.

Experiments with this technology have shown about 96 percent recovery in electronics within 15 minutes, with minimal power consumption. This means that not only can “healing” take place in short order when needed, but with the heating elements localized and the consequent reduction in wasted heat, the power consumption will be far lower than in traditional spacecraft designs. This technology also allows different components to be operated at ideal temperatures for their optimal function, which may vary from one part to another. This would not only maximize performance, but would

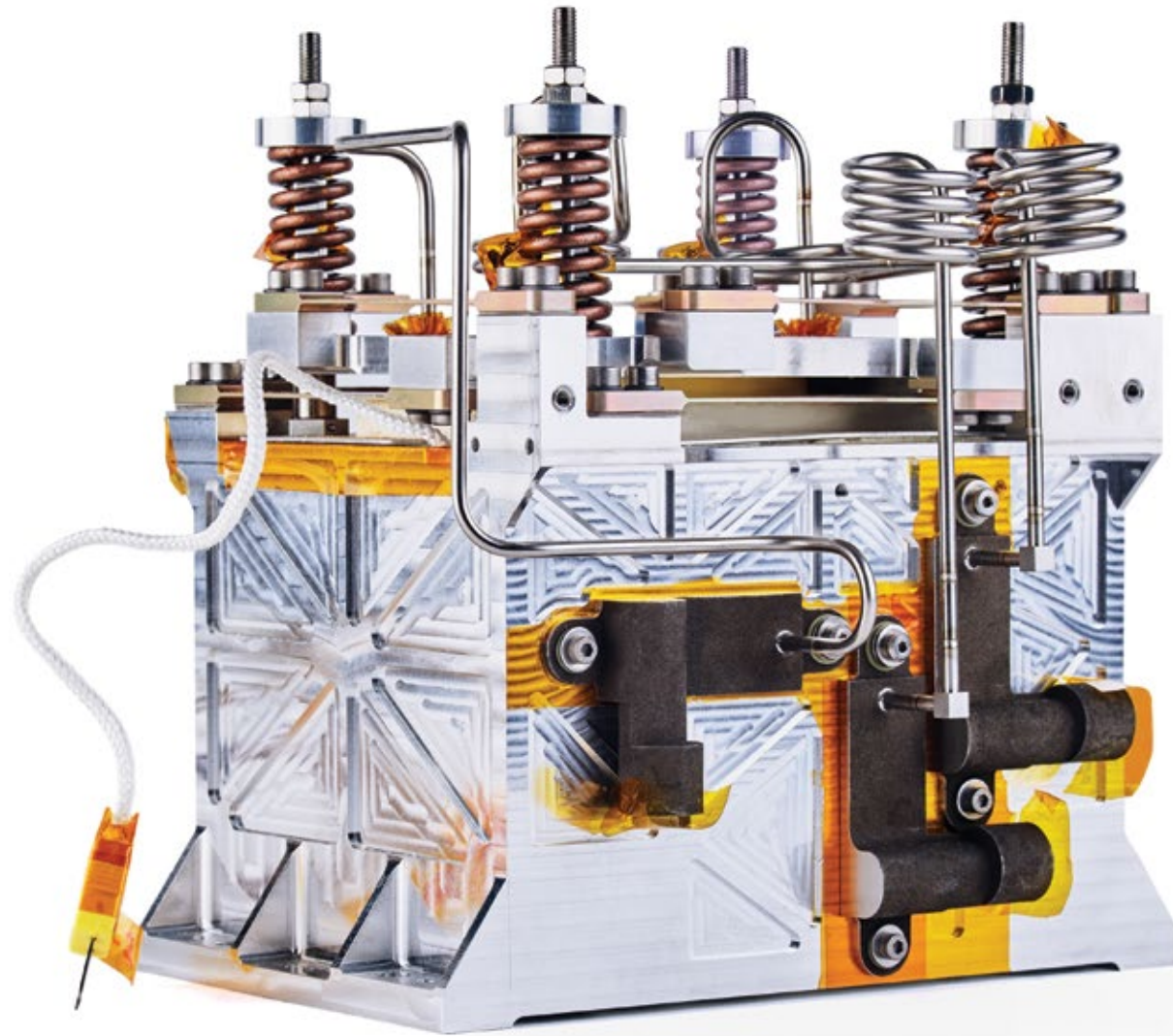


Diagrammatic cross-section of self-heating electronics.

minimize electronic noise emitted by larger heating assemblies.

This technology shows promise for not just cold environments like Europa and Enceladus, but anywhere beyond the Earth’s magnetosphere where spacecraft must function in radioactive environments. Furthermore, this technology can greatly prolong the lifespan of devices in these environments by regenerating radiation damaged devices.

**SPACECRAFT OPERATING IN COLD, HIGH-RADIATION ENVIRONMENTS REQUIRE HEATING TO ACHIEVE MISSION GOALS. A NETWORK OF TINY HEATERS AND SENSORS COULD EFFICIENTLY PROVIDE THE NEEDED HEATING, AND ALSO “HEAL” RADIATION DAMAGE**



TH/14

# MARS HAS MOXIE!

For humans to make the long trek to Mars and back, a critical challenge is the utilization of resources found on the planet. An experiment to generate oxygen from Martian carbon dioxide will travel aboard the Mars 2020 rover, and it's called MOXIE.

MOXIE stands for Mars OXYgen In-situ resource utilization Experiment, and its sole purpose is to demonstrate the ability to generate pure oxygen electrochemically from the Martian atmosphere.

Mars has an abundance of carbon dioxide (CO<sub>2</sub>) in its atmosphere, about 96 percent, from which oxygen can be created. Oxygen is obviously valuable for human survival on the Red Planet, as well as for supplying oxidant for propellant to return robotic spacecraft such as a sample return vehicle. An electrochemical reduction is all that is needed to generate oxygen from Martian air.

The 33-pound MOXIE will be mounted underneath the front right side of the Mars 2020 rover. The process it uses is called solid oxide electrolysis, and is based on the fact that when heated, certain ceramic oxides become ion conductors. A series of ten membrane-electrode combinations, each consisting of a thin ceramic oxide membrane sandwiched between two electrically charged porous electrodes, are compressed and packaged into a thermally insulated and heated box. This box, coupled to a Mars atmosphere pump, and the operational electronics are inside the MOXIE housing.

The CO<sub>2</sub> molecules pumped into the system are dissociated into carbon monoxide and oxygen atoms by the catalyst on the cathode. Simultaneously, the oxygen atoms are reduced electrochemically to oxide ions (O<sup>=</sup>) which are transported across a thin zirconia membrane to another catalyst at the anode. In this electrode the oxide is electrochemically oxidized back to oxygen atoms which, in combination with other oxygen atoms forms molecular oxygen (O<sub>2</sub>), the end goal.

MOXIE is tasked to create about 8 grams of oxygen per hour — just a tiny amount, but sufficient to validate the technology. This is a subscale experiment, and its success could be followed by a larger device capable of producing and storing oxygen for future use by a Mars Ascent Vehicle for potential soil sample return, and to later prepare for human spaceflight needs.

MOXIE represents the first time such a complete system has been designed to operate autonomously, and to withstand the rigors and stresses of launch, interplanetary transit, and landing on Mars — no small task. This forward-looking approach to planetary exploration is a critical step toward future missions to the Red Planet.

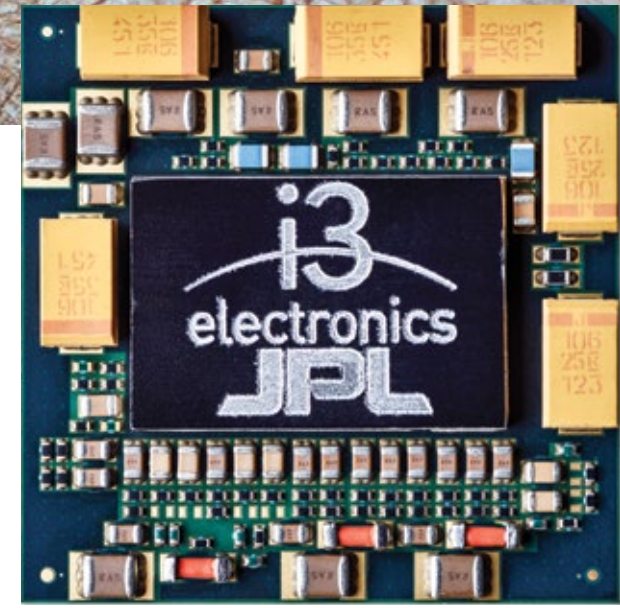
MARS LACKS BREATHABLE OXYGEN, WHICH WILL BE CRITICAL FOR THE EXPLORATION OF MARS. A NEW TECHNOLOGY EXPERIMENT WILL SOON LAND ON THE RED PLANET TO PAVE THE WAY FOR PRODUCING IT FROM MARTIAN ATMOSPHERE



Opposite page: detail of heated solid oxide electrolyzer.  
Right: MOXIE's membrane-electrode combinations between porous electrodes in a sandwich-like structure.

TH/15

# SURVIVING EUROPA



Europa is a cold environment, with *high* temperatures of minus 260 degrees F (-162 C) at the equator. And that’s at local “high noon.” In addition, any spacecraft sent to Jupiter and its moons would also be bathed in high radiation, so operating a robotic lander there requires some exotic electronics.

Research is underway to develop a controller for a robotic arm that can operate in the harsh Europa environment. This is part of a more general move towards a distributed architecture that can result in a mass and power savings of as much as two-thirds over current designs. However, distributing electronics out to the actuators requires them to survive Europa’s cold, high-radiation environment without the protection of a centralized, shielded hotbox.

Radiation in the Jovian system is far more punishing than even in interplanetary space. These electronics must therefore be hardened against the effects of high-energy electrons in the mega-electron-volt range and radiation doses of up to 300 kilorads—enough to cook traditional electronic components in short order—and able to survive Europa’s bitter cold.

LANDING ON EUROPA WILL BE A CHALLENGING MISSION EVENT, BUT OPERATING THERE WILL BE EQUALLY AS DIFFICULT. ELECTRONIC SYSTEMS MUST BE DESIGNED TO SURVIVE AND OPERATE IN UNIMAGINABLY COLD TEMPERATURES

The energy required to keep the electronics warm could be reduced by allowing the electronics to be stored at the ambient environment and only heated prior to operation. This means that there would be more of both mass and power for science instruments.

The primary breakthrough is in the electronics packaging technology, which results in a factor-of-ten reduction in the size of the controller electronics compared to its predecessors, while tolerating 15 times more radiation than the Curiosity Mars rover.

Elements of this system have been successfully tested over 100 cycles at temperatures down to minus 310 degrees F (190 C). An end-to-end system should be ready for testing as a complete unit by 2020, and is baselined in the Europa Lander mission concept.

This technology is being developed in partnership with i3 Technologies.



New modules above are 10 times smaller in volume over conventional module packaging. Both components shown above at relative size.



Opposite page: High Density Interconnection System in Package. The resolver module is designed to measure position of actuators.



TH/16

# ASTRO-DATA TOOLS AID CANCER RESEARCH

Few disciplines experience the variety of data challenges faced by planetary science. Sifting through vast quantities of incoming data, and detecting meaningful patterns, is an immense and complex undertaking.



## NEW SOFTWARE ENABLING SOPHISTICATED MERGING AND MINING OF IMMENSE VOLUMES OF DATA DEVELOPED FOR PLANETARY SCIENCE CAN BE APPLIED TO CANCER RESEARCH

Such data-handling challenges have long been an area of expertise for JPL, and the benefits of this ongoing analytical development are now being adopted to advance cancer research.

Traditionally, research centers have independently developed unique analysis systems for the identification of cancer biomarkers based on their own research needs. Typically, these systems are incompatible and do not scale well to multiple data sets. The overwhelming amount and types of data now available defy analysis using such systems. Researchers have successfully applied software developed for planetary data analysis to the problem.

Both research areas face similar challenges due to the overwhelming amounts of data. One example of how the application of planetary data handling can enhance cancer research is the identification of certain features in pathology images, across multiple data sets, that can enable detection. This is

similar to how astronomical phenomena are detected and analyzed.

NASA's Planetary Data System (PDS) is a distributed data network that archives data collected by planetary missions, and has been highly effective at allowing researchers distributed across the world to access decades of data collected from a multitude of missions. Working with a consortium of biomedical investigators who share anonymized data on cancer biomarkers and chemical or genetic signatures related to specific cancers, PDS software has applied planetary data reduction techniques, including AI and machine learning, to improve speed

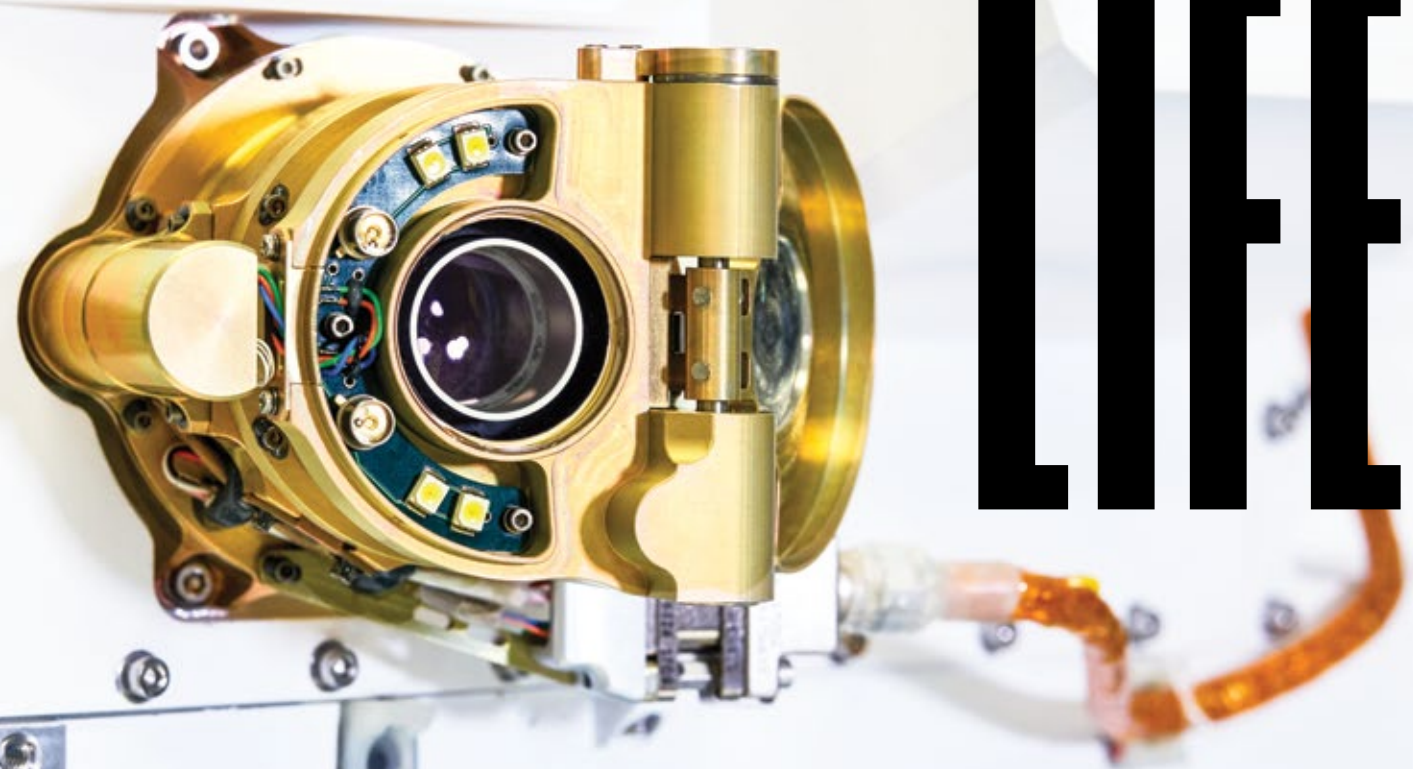
and accuracy in cancer research.

The net result has been to automate analysis in cancer research, and provide a variety of research centers with access to better tools. This dual-use system allows cancer researchers to pool their research into one large, searchable network that promotes collective research that will lead to early diagnosis of cancer and cancer risk. This work recently led to new FDA approved biomarkers that have been used in more than a million patient diagnostic tests worldwide.

JPL partnered with the Dartmouth Medical School on this effort, which was funded by the National Cancer Institute's Division of Cancer Prevention.

TH/17

# SLEUTHING FOR LIFE



On the 100th anniversary of C.V. Raman's pioneering investigation of light scattering by molecules, JPL's Raman spectrometer will utilize this technique using a deep UV laser to create maps of the distribution of organics on the Martian surface.

The Mars 2020 rover will undertake state-of-the-art science to help us further understand the nature and history of Mars. In the past, Mars appears to have had all the conditions needed for life, including liquid water, energy sources, and organic molecules.

Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC), is an instrument designed to find and characterize organic molecules. SHERLOC is an arm-mounted, deep-ultraviolet resonance Raman and native fluorescence spectrometer combined with microscopic imaging capabilities. SHERLOC will be capable of identifying organic material and mapping the distribution of organics with respect to visible images created by the Wide Angle Topographic Sensor for Operations and eNginneering (WATSON) camera, which is similar to the MAHLI camera that flew on the Curiosity rover.

Once the Mars 2020 robotic arm is positioned near a target of interest, SHERLOC will utilize a mirror that moves a 100-micron laser spot over

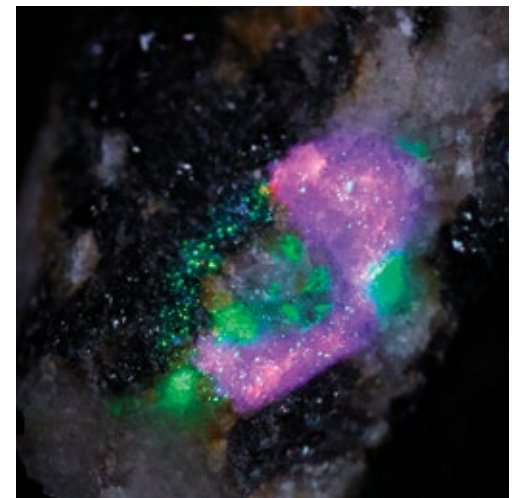
the surface in order to identify shifts in the photon energy resulting from either fluorescence-induced emission or Raman scattering. The backscattered light is collected and passed through a miniature spectrometer. The Raman measurement can identify minerals and chemicals such as carbonate, sulfates, perchlorates, and aliphatic organic molecules such as amino acids, lipids and proteins. Other organic molecules that have carbon rings, known as aromatics, will be identified via fluorescence.

Creating molecular maps that can be correlated with surface texture allows for analysis of the provenance of organic molecules. These correlated chemical and molecular maps allow researchers to combine them with data from the PIXL and SuperCam instruments in a truly collaborative way.

SHERLOC will enable the Mars 2020 rover to identify the most promising surface samples to cache. Then, within a decade, promising samples of the Martian surface could potentially be brought back to our planet to continue the search for life on the Red Planet.

Opposite page: engineering model of the SHERLOC instrument undergoing tests in the laboratory.

THE SHERLOC INSTRUMENT, SCHEDULED TO FLY ON THE MARS 2020 ROVER, WILL IDENTIFY SURFACE ORGANICS AS PART OF THE SEARCH FOR SIGNS OF LIFE ON MARS



Above: image taken by the SHERLOC instrument of a test target showing the variation of composition across the sample.

TH/18

# BIG POWER IN A SMALL PACKAGE

Conventional batteries are challenged by the low temperatures encountered in the outer solar system. New hybrid energy storage systems that are capable of operating in colder environments and can provide bursts of high power on demand may be the perfect solution for this problem.

One of the major challenges of deploying spacecraft into the outer solar system is the limited thermal operating range of conventional energy storage technologies. Temperatures encountered in these environments are much colder than near Earth, causing a loss of efficiency in conventional spacecraft batteries. Additional spacecraft heaters are often needed to keep the batteries warm, further increasing power demand. This ultimately increases the mass and volume of the power system. In addition to these demands, technologies such as advanced transponders, radars, thrusters, lasers, and other payloads also require bursts of even higher power. These intense power demands at low temperatures not only deplete the available energy of the battery more rapidly, but also increase the degradation rate of conventional battery chemistries such as lithium-ion (Li-ion). Battery storage degradation shortens mission life and can jeopardize success.

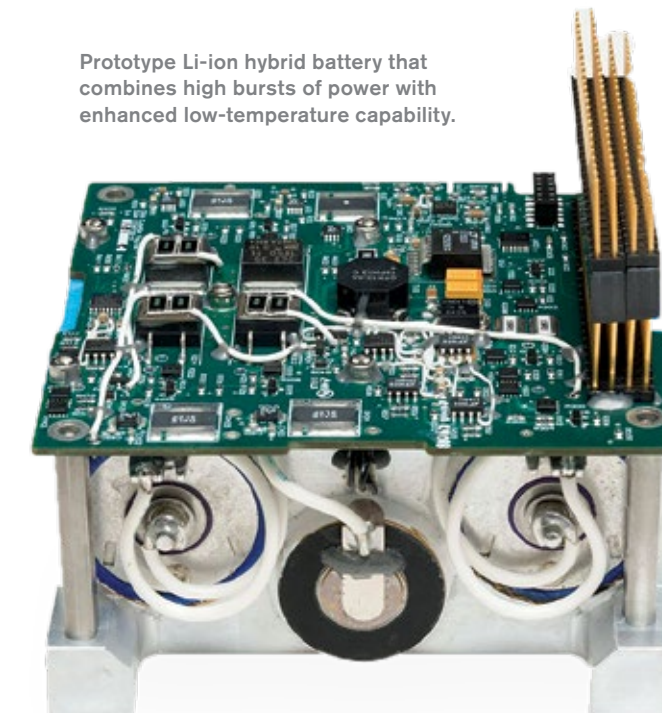
New hybrid battery designs combine both the benefits of high *power* density from super-capacitors, and high *energy* density from Li-ion batteries. To further enhance performance at lower temperatures, Li-ion cell technologies have been modified with novel electrolyte formulations to provide high energy and

long life. These batteries can function down to about minus 58 F (-50 C), which effectively eliminates system complexity to provide battery heating in many mission environments. Along with capability of providing extremely high bursts of power, the hybrid energy storage system is a major advance for electricity-hungry spacecraft operations in the outer solar system and beyond.

Prototypes of these hybrid batteries were recently flight demonstrated on an experimental CubeSat called CSUNSat1 developed by California State University, Northridge. Battery performance at low temperatures and during high-current bursts were successfully demonstrated. This hybrid battery design shows great promise for big power in a small package, to allow exciting new science.

**TO ENABLE FUTURE MISSIONS TO OUR OUTER SOLAR SYSTEM, A NEW HYBRID BATTERY TECHNOLOGY CAPABLE OF OPERATING AT COLDER TEMPERATURES AND AT HIGHER POWER DENSITIES HAS BEEN DEVELOPED AND DEMONSTRATED IN SPACE**

Prototype Li-ion hybrid battery that combines high bursts of power with enhanced low-temperature capability.



TH/19

# BREATHE EASY



This compact and scalable system can extract oxygen from the Martian atmosphere at lower temperatures using smaller packaging and less energy than other available technologies.

Caltech and JPL researchers are developing a new approach to produce oxygen from the Martian atmosphere for both life support and propulsion. This technology involves a process utilizing catalysts to convert Martian carbon dioxide (CO<sub>2</sub>) into oxygen at Mars ambient temperature—a less power-hungry technique than previous approaches that required high temperatures.

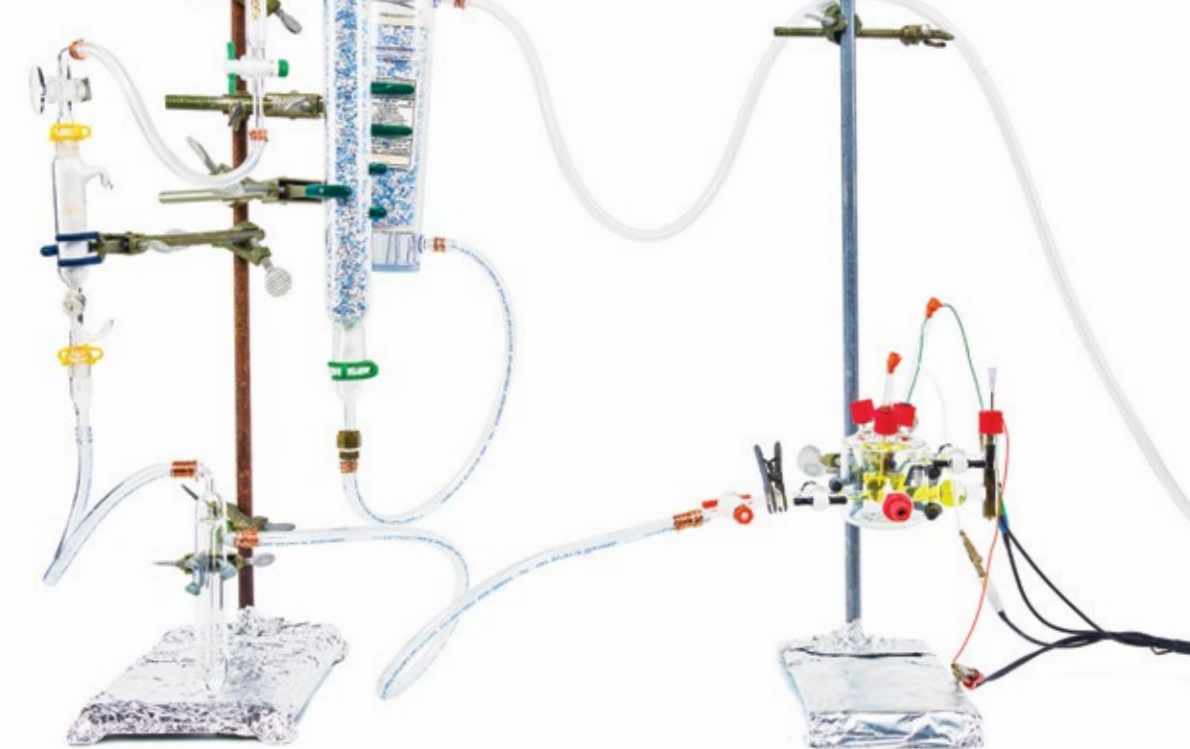
Oxygen generation is accomplished in two separate steps using active catalysts. First, the atmospheric CO<sub>2</sub> is reduced to water using electrochemical methods and a molecular metallic catalyst in an acid solution. The catalyst attaches to and activates CO<sub>2</sub> molecules to generate water using protons and energy—no noticeable byproducts or unwanted side reactions are created in the process. The water is then oxidized electrochemically to produce oxygen by using a nickel-iron or iridium nanostructured catalyst. These materials

are shaped at the nano-scale to create features that, at high oxidation states, bind water molecules and catalyze the release of oxygen with low energy input.

This technology was demonstrated on a small scale in early 2018. This new design uses up to 85 percent less energy than state-of-the-art methods that require high-temperatures. It produces pure

oxygen that requires no gas separation and purification. A three cubic-foot backpack could potentially produce up to 300 grams of oxygen per hour, adequate for human needs. In addition to being an essential component of life support, the oxygen produced could be used as an oxidizer in rocket propulsion for trips back to Earth by human or robotic spacecraft.

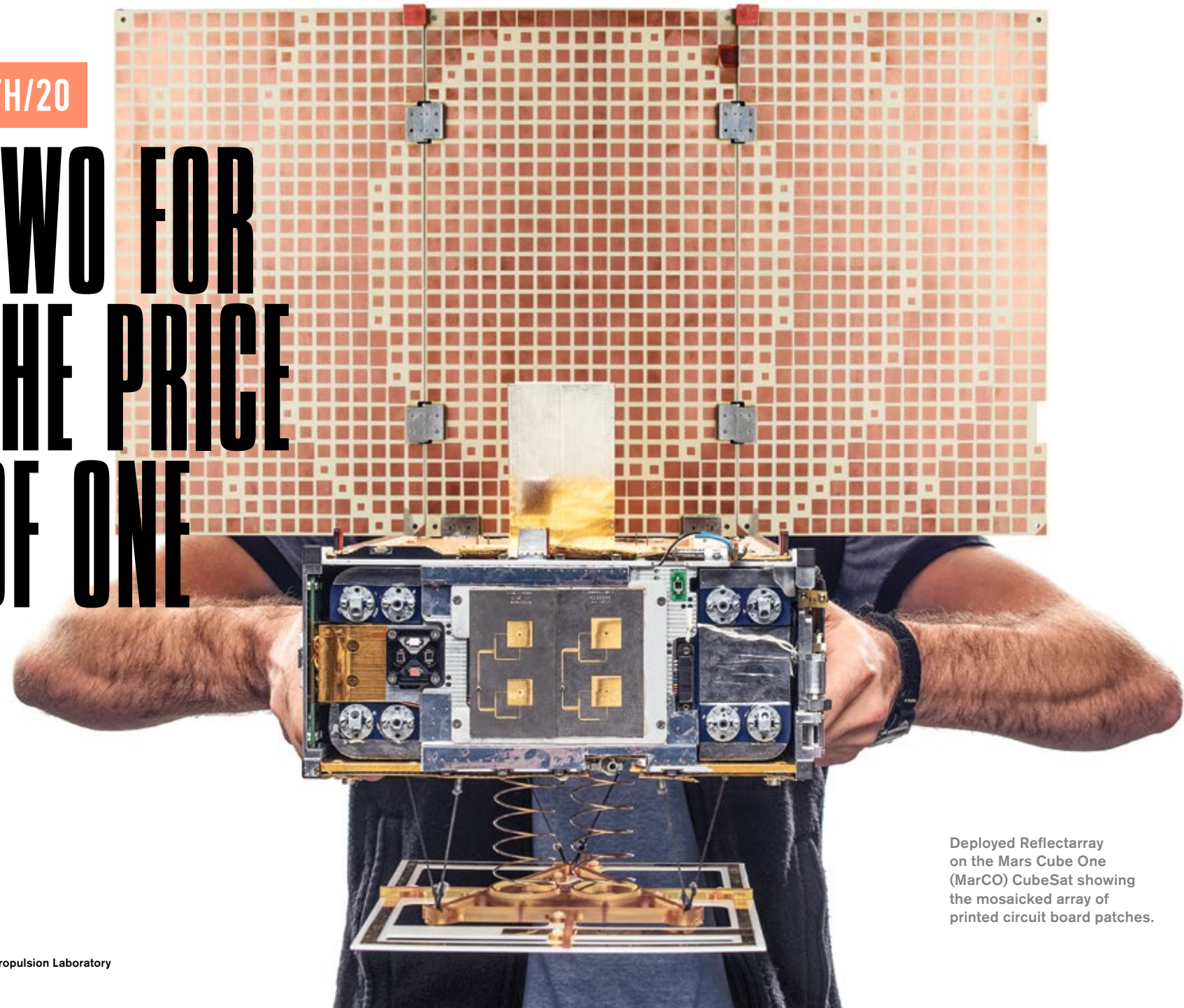
Opposite page and above: laboratory test of reaction using a catalyst to convert carbon dioxide to oxygen at ambient temperature.



**A NOVEL NEW TECHNOLOGY CAN GENERATE UNLIMITED SUPPLIES OF OXYGEN FROM THE MARTIAN ATMOSPHERE TO SUPPORT FUTURE MISSIONS TO THE RED PLANET**

TH/20

# TWO FOR THE PRICE OF ONE



Deployed Reflectarray on the Mars Cube One (MarCO) CubeSat showing the mosaicked array of printed circuit board patches.

Improved designs for compact antennas suitable for small spacecraft has been an area of intensive development for decades, but true breakthroughs are rare. Reflectarray, a mosaicked antenna design, represents just such an advancement.

Most modern spacecraft requiring high-data-rate communications use high-gain antennas that are parabolic reflectors, and are difficult and costly to develop and deploy. Even in the stowed configuration, these assemblies can be bulky.

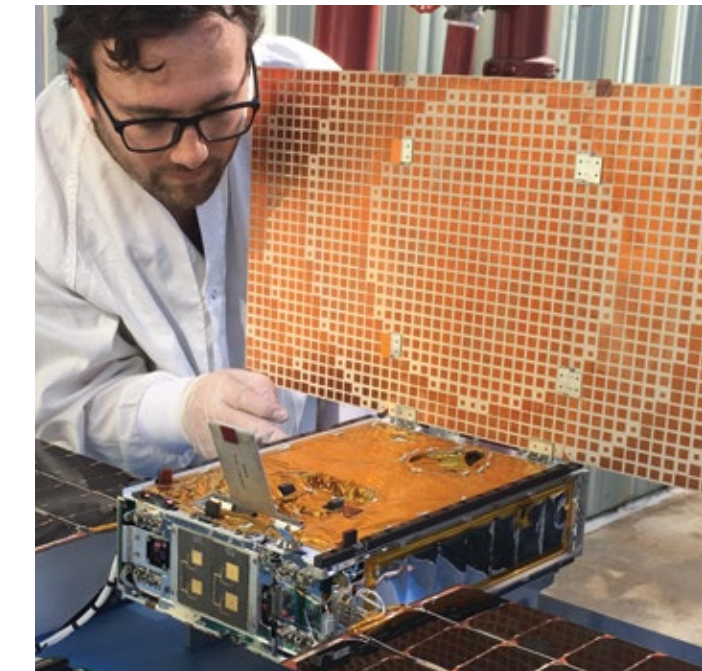
Engineers have developed low-cost, lightweight, high-gain spacecraft antennas that stow in a small volume. The resulting technology is called a Reflectarray, and is based on a new approach using an array of printed circuit board patches of varying sizes. Reflectarray is a flat-panel X-band antenna engineered to direct radio waves the way a parabolic dish antenna does. The reflecting surfaces employed in these antennas are characterized by a surface impedance that can be synthesized to produce a variety of 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 design enables a flat antenna architecture that folds into a thin, easily stowed package. To achieve the flatness required for an antenna, designers devel-

oped unique new co-cured multi-layer composite circuit boards that are both thin and stiff. Such designs enable antennas to be integrated back-to-back with a solar panel, thereby creating a combined high-gain antenna and high-efficiency solar array in a single deployable system.

Reflectarray was first proven in March 2018 on the Integrated Solar Array and Reflectarray Antenna (ISARA) CubeSat mission. The solar cells on the back side of the antenna generate about 24 Watts of spacecraft power. The flat design allowed the antenna to be stowed in the “dead space” between the satellite launch rails that would have otherwise been left empty. The Mars Cube One (MarCO) mission, launched with the InSight mission in May 2018 and the first CubeSat flown to Mars, also adopted Reflectarray technology. The MarCO antenna consumes only about four percent of the spacecraft volume and weighs less than two pounds (1 kg).

Reflectarray technology is transforming how small spacecraft are able to communicate with, and observe, the Earth and beyond.

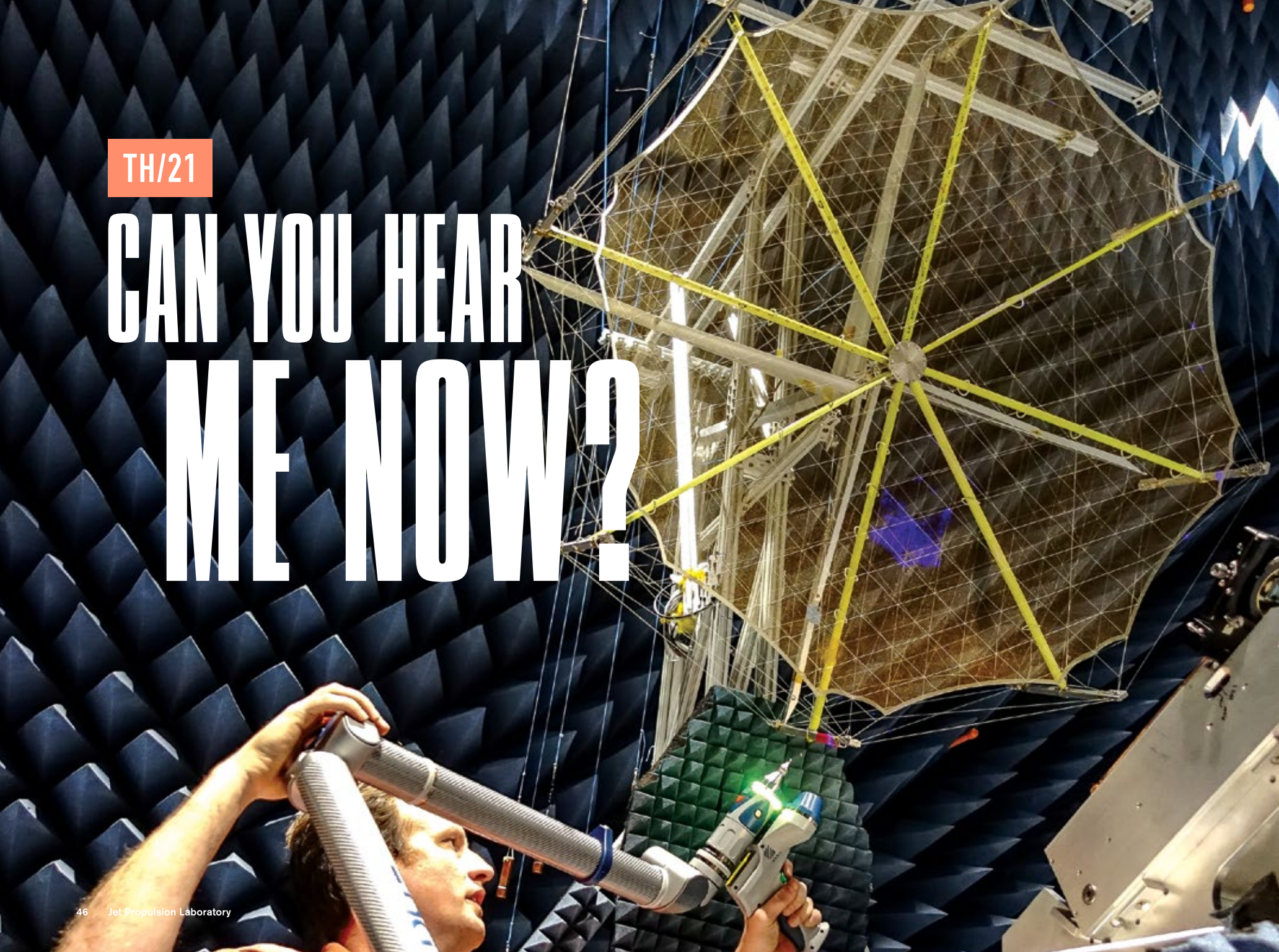


A REVOLUTIONARY NEW HIGH-GAIN ANTENNA CALLED REFLECTARRAY COMBINES THE SIMPLICITY OF A REFLECTIVE ANTENNA WITH THE PERFORMANCE VERSATILITY OF AN ARRAYED ANTENNA



TH/21

# CAN YOU HEAR ME NOW?



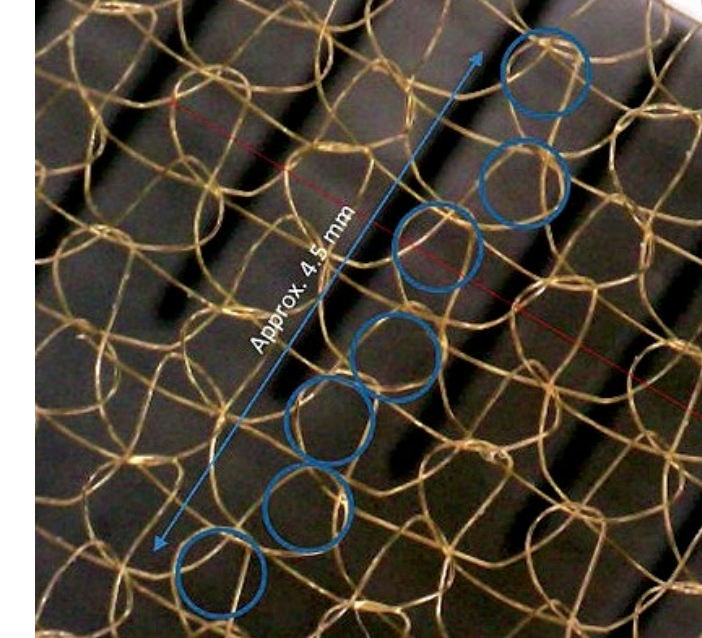
Achieving high-resolution radar in Earth's orbit and deep space will require equipping them with large, high gain antennas that can fit in compact volumes for launch. New antenna designs have achieved high-resolution radar and high-bandwidth communication in a small form factor.

A team from JPL, UCLA and TENDEG has designed a deployable Ka-band antenna called KaTENna that fits within a CubeSat-sized space for launch, then fans out like an umbrella when deployed. KaTENna will work for radar missions, as well as Earth orbital and deep space communication. This is true multi-mission technology.

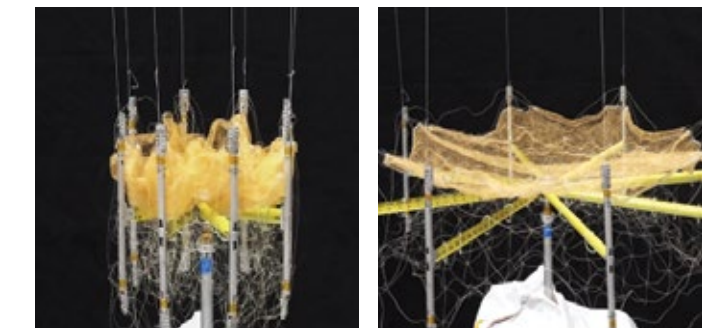
The ingenious antenna design is based on the tensegrity (tensional integrity) concept, in which the parabolic surface is created by tensioning mirror-imaged nets. KaTENna improves on earlier designs by replacing the perimeter truss with a unique tensioned-cord wheel and spoke system. A set of steel carpenter tapes deploy from the central hub to form spokes, which support a reflector ranging from three to fifteen feet (1-5 meters) in diameter. This system can be stowed compactly and

still achieve excellent surface accuracy, and has the benefit of imparting no angular momentum to the spacecraft during deployment. Another advantage of KaTENna is that it uses an offset-fed reflector. This feature eliminates blockage and dramatically simplifies the problem of locating the feed close to the transmitter/receiver on the spacecraft.

This antenna is compatible with NASA's Deep Space Network at highly useful Ka-band frequencies. The current 3-foot (1m) diameter antenna folds down to a 4-by-4-by-12 inch (10x10x30cm) package compatible with a 3U CubeSat form factor. This stowable antenna has demonstrated an efficiency of 60 percent, which is close to the performance of rigid non-deployable antennas in Ka-band. A larger six-foot (2m) diameter version of KaTENna is being developed.



**NEW DESIGNS FOR DEPLOYABLE ANTENNAS SHOW HIGH RELIABILITY AND INCREASED BANDWIDTH IN A SMALL, EFFICIENT PACKAGE FOR USE IN DEEP SPACE MISSIONS**



Above: detail of KaTENna mesh.  
Below: two stages of KaTENna deployment.



TH/22

# SUPERSONIC CHUTE

Mars landers must deploy parachutes at supersonic speeds. The behaviors of these enormous canopies is incredibly difficult to model, but engineers have bridged the gap between computer analysis and Martian landings with test flights high into Earth's atmosphere.

Mars-bound landers rely on parachutes that must be extremely large, yet very strong, to do their job in the thin Martian atmosphere. It is, however, very difficult to test large parachutes on Earth at the required supersonic speeds. Wind tunnels are not powerful enough, and Earth's lower atmosphere is too dense to stand-in for the thin Martian atmosphere. Engineers have long sought a way to simulate Martian conditions to assure successful mission performance.

ASPIRE, which stands for the Advanced Supersonic Parachute Inflation Research Experiment, is testing the parachute design for the upcoming Mars 2020 rover, a one-ton mobile laboratory. The parachute on the Mars Science Rover Curiosity worked well in 2012, but for Mars 2020 mission designers wanted to gain more confidence in how these large parachutes behave under the shocks and stresses caused by supersonic deployment above the Red Planet.

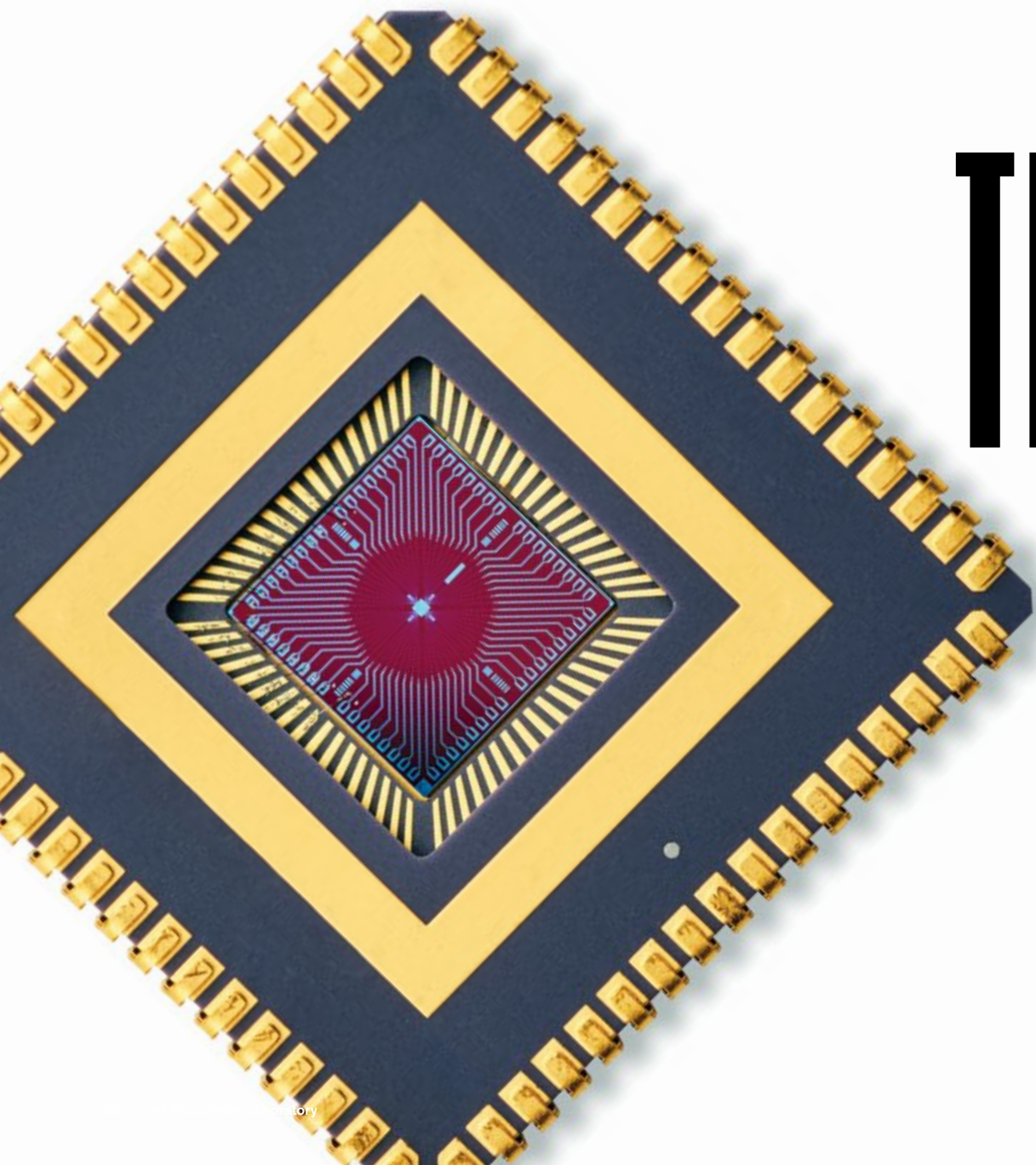
Computer modeling offers some insight, but parachute behaviors are notoriously difficult to predict and they must be tested in something close to actual flight conditions. The ASPIRE team tested a 71-foot parachute by flying it into Earth's thin upper atmosphere on a rocket, then opening it at an altitude of 26 miles, where the air is about the same density as is found on Mars, about 1/100th that of Earth's at sea level.

Mars 2020 will enter the Martian atmosphere at a speed of about 12,000 mph (19,300 kph). After the heat shield is jettisoned, the supersonic parachute will slow the spacecraft from a speed of over 1800 mph (2900 kph) to a more leisurely 170 mph (273 kph), when the Sky Crane system will complete the touchdown. Successful high-altitude testing of the parachute for Mars 2020 has validated the performance of the parachute design, which is key to the success of this unprecedented mission of astrobiology and discovery.

Right: a NASA sounding rocket launch carried ASPIRE to a maximum altitude of 32 miles (51 kilometers). The parachute unfurled shortly thereafter, while ASPIRE was traveling significantly faster than the speed of sound.

HIGH-ALTITUDE TESTS  
HAVE BEEN CONDUCTED  
IN EARTH'S UPPER  
ATMOSPHERE TO  
BUILD CONFIDENCE  
IN SUPERSONIC  
PARACHUTES FOR  
LANDING MARS 2020





TH/23

# TINY TECH HUGE IMPACT

Nanotechnology involves manipulation of matter at the atomic or molecular level to fabricate materials and structures with at least two dimensions having nano-scale patterning. These materials have unique qualities that can significantly enhance space exploration.

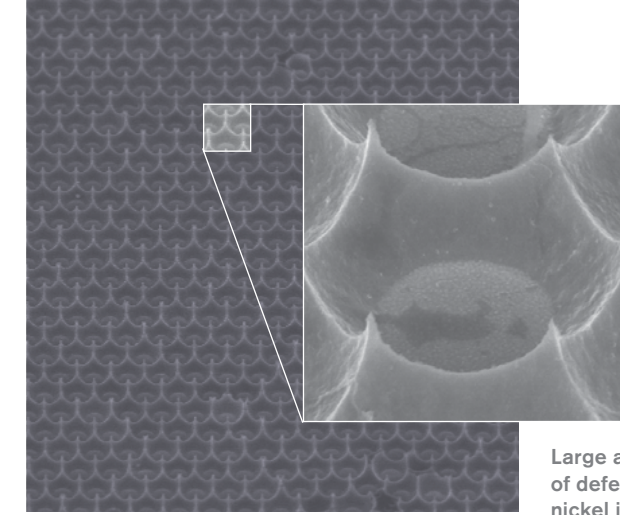
The miniaturization of individual components as well as the pursuit of larger system-level strategies to create miniaturized systems will enable ever more exciting missions. Many of NASA's future goals will become achievable with the benefits of nanotechnology.

In sensor technology, nanotech has pushed the state of the possible. Superconducting Nanowire Single Photon Detectors or SNSPDs are now the highest performing detectors spanning the ultraviolet to mid-infrared range of the electromagnetic spectrum, where some of the most compelling science resides. They have led the way in detection efficiency, time resolution, active area, and dark counts. These detectors are an attractive technology for ultra-low-noise mid-infrared focal plane arrays for future space telescopes. This technology can also be used as telecommunications sensors, and arrays were flown on the Lunar

Laser Communication Demonstration mission in 2013, and will be used on the ground terminal of the Deep Space Optical Communication project being planned for 2022.

Nanotech is also a critical part of creating extreme environment electronics for lander mission concepts for Venus, Titan, or Europa. It has enabled the development of low-voltage field-emission electron sources that can be integrated with patterned electrodes to produce chip-scale vacuum electronic devices. The performance of these devices is approaching that of their solid state counterparts, and they have the added advantage of functioning in hostile environments.

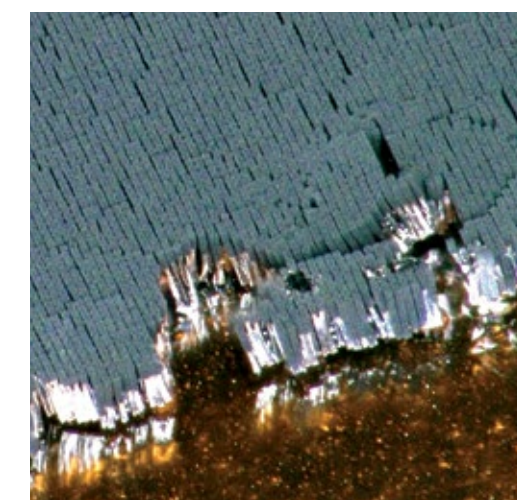
On the materials side, examples of useful nanotech include biomimetic adhesives made from carbon nanotubes that mimic the feet of gecko lizards for robots that can climb steep and even inverse surfaces. Also, bulk metallic glass structures are useful for robotic applications in cold environments due



Large array of defect-free nickel inverse opal emitter tips with tip radii of less than 10 nm, used for field emission devices.

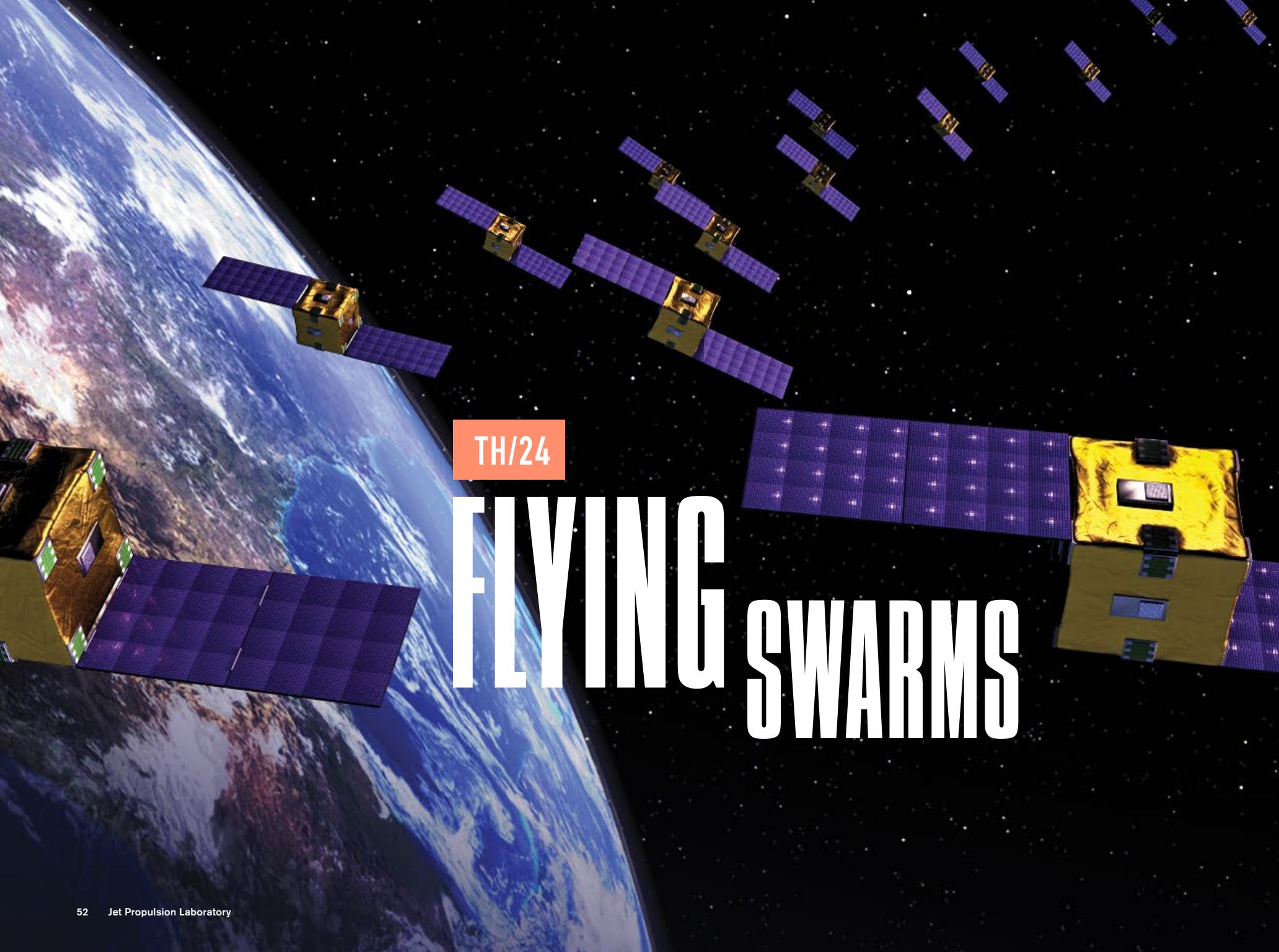
to their intrinsic self-lubricating qualities. Both will help to enable the exploration of complex, rugged terrain on other planets and icy moons.

Successes have also been achieved with nanotechnology in areas such as cryogenic thermal radiators, miniature X-ray sources, high-power and low-temperature energy storage, and qubit processors for quantum computing. All these devices are fabricated at the nanometer scale, and allow for much smaller and more robust machines that will greatly expand our space exploration horizons.



Optical image showing a carbon nanotube array adhered to polyimide film.

**FROM ULTRA-SENSITIVE DETECTORS TO STICKY-FOOTED ROBOTS TO ELECTRONICS THAT CAN OPERATE IN INCREDIBLY HOT OR COLD ENVIRONMENTS, NANOTECHNOLOGY IS ADDING NEW CAPABILITIES FOR THE EXPLORATION OF THE UNIVERSE**



TH/24

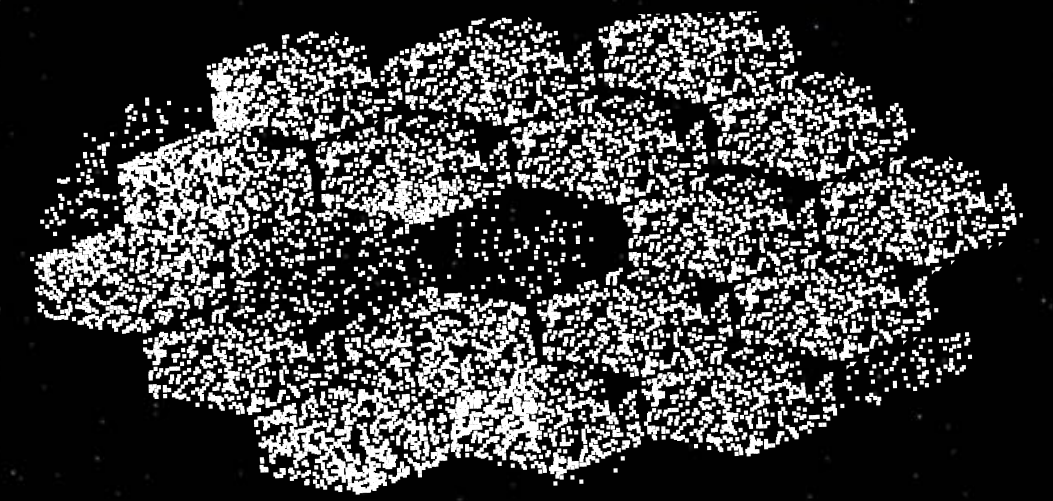
# FLYING SWARMS

JPL is developing swarming technologies that can revolutionize space exploration. Teams of spacecraft can cooperate to form virtual structures such as synthetic apertures, and can perform distributed measurements not possible with a single spacecraft.

Spacecraft swarms can deliver a comparable or greater capability than a monolithic system with the benefit of greater flexibility and robustness. A group of small spacecraft armed with various sensors can adapt to new mission requirements. The system is more fault tolerant and easier to maintain since spares can be included in the mission, allowing a faulty spacecraft to be quickly replaced. Swarms of spacecraft can therefore take higher risks while exploring more challenging science, since no single spacecraft is critical to mission success.

A collaboration between JPL and Caltech's Center for Autonomous Systems Technology (CAST), has developed and demonstrated distributed, collaborative architectures and algorithms for onboard guidance, navigation, and control enabling autonomous reconfigurations, proximity operations, and autonomous station-keeping of swarm systems. These algorithms are applicable to small swarms of two-to-

ten spacecraft, as well as to very large formations, that can reach into the thousands. While for smaller size swarms, deterministic guidance path planning and collision avoidance algorithms have been demonstrated to achieve a desired configuration. For larger formations, stochastic guidance algorithms taking advantage of the law of large numbers has been shown to be the effective methodology and with much less computational requirements. These algorithms can be applied to swarms of boats on the ocean, drones in the air, as well as multiple underwater vehicles. In space, teams of formation flying spacecraft can form a virtual telescope, act as a synthetic aperture for radar remote sensing, or as collective reflectors.



Above: 35,000 femtosats in formation to create a large telescope mirror. The open patch to left of center shows the swarm self-reconfiguring following an encounter with orbital debris.

**LARGE NUMBERS OF TINY SPACECRAFT WORKING TOGETHER FOR THE EXPLORATION OF THE UNIVERSE CAN BE A GAME CHANGER IN REDUCING COSTS AND FOR ALLOWING MISSIONS THAT CAN BE IMPOSSIBLE TO DO WITH A SINGLE, MONOLITHIC SPACECRAFT**

Opposite page: illustration of femtosats in string-of-pearls formation.

TH/25

# CAST-ING FOR SUCCESS

The Center for Autonomous Systems and Technologies, or CAST, has been formed to explore autonomous systems capable of undertaking complex missions without human involvement.

The goal of this partnership is to advance the science of autonomy through the fusion of technological advances in computation and algorithms joined with robotics. Members of JPL's leadership and technical organizations serve on the steering and scientific advisory committees.

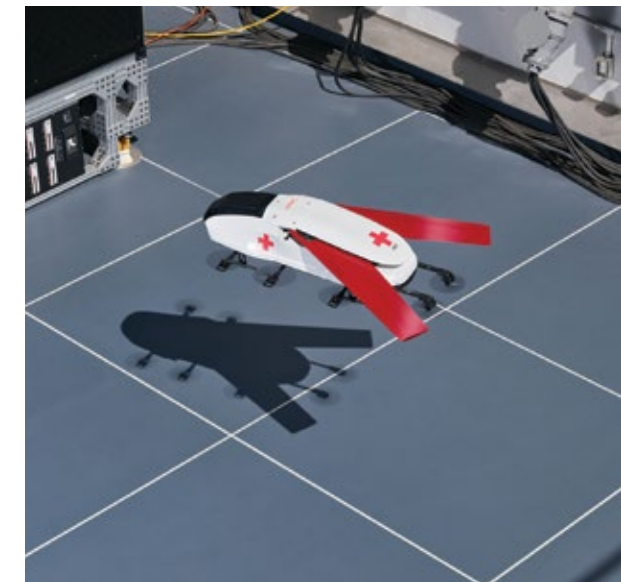
CAST has initiated a series of five "moonshot" programs: *Explorers*, *Guardians*, *Transformers*, *Transporters* and *Partners*. Each represents an area ripe for significant innovation and technological advancement in autonomy. *Explorers* focuses on robotic mobility for surviving, navigating, and operating in unknown and complex environments with applications in planetary exploration and terrestrial surface, underwater and aerial exploration. *Guardians* is focused on monitoring and responding to dynamic events such as earthquakes and tsunamis by surveying, gathering and distributing critical information that would serve as a multiplier of the effectiveness of human responders by providing a better picture of the environments in which they are working. *Transformers* investigates swarms of robots that could autonomously transform their shape and function to meet specific needs in orbital

assembly, space telescopes, communication and science observations, and for use on planetary surfaces for the deployment, construction and the assembly of complex structures. *Transporters* concentrates on all-weather aerial platforms that can operate in turbulent atmospheric conditions, which could augment the abilities of flying ambulances or medical delivery drones as well as planetary science missions. Finally, the *Partner* moonshot will develop autonomous robots that will assist the sick and elderly, act as physician surgical assistants and in other applications that will improve function, mobility and quality of life for people worldwide.

This facility utilizes 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 single spacecraft and for multiple spacecraft operating 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.

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.

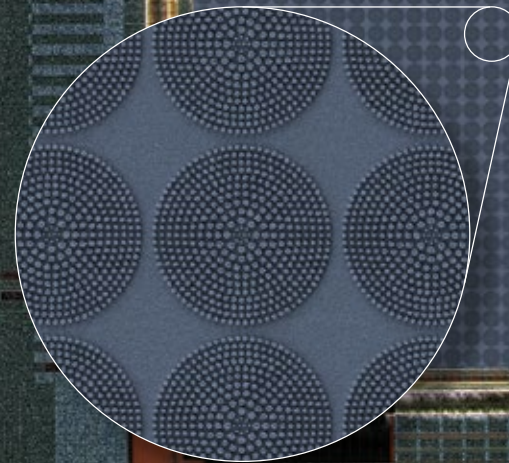
THE BEST RESEARCH OCCURS THROUGH COLLABORATION, AND A NEW PARTNERSHIP BETWEEN JPL AND CALTECH RESEARCHERS BRINGS TOGETHER TWO CENTERS OF INNOVATION IN TECHNOLOGY TO SOLVE COMPLEX AUTONOMY PROBLEMS ON EARTH AND IN SPACE



Opposite page: researchers at CAST's state-of-the-art facility prepare for a simulation of autonomous systems operating in formation. Right: an autonomous ambulance is flight tested at the CAST aerodrome.

TH/26

# CHANNELING LIGHT



Much of NASA's scientific inquiry demands increasingly sensitive and accurate detectors, especially in the infrared part of the spectrum, which is critical to Earth observation, planetary science and astrophysics.

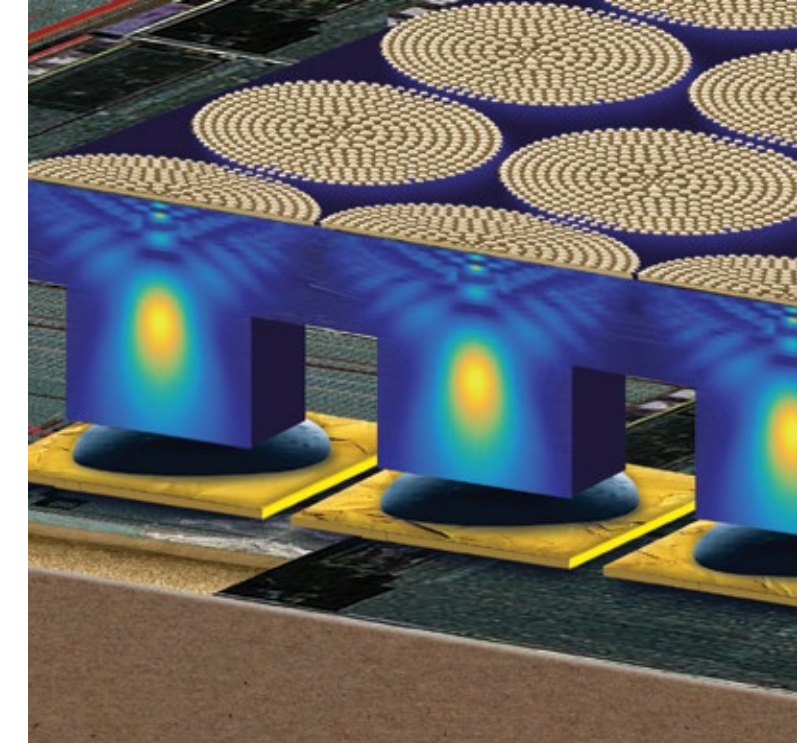
To achieve high sensitivity in the mid- to long-wavelength infrared, detector arrays are typically cooled to cryogenic temperatures to reduce thermally induced "dark currents" that compete with the signal. Cooling to such low temperatures requires the use of vacuum-insulated vessels containing finite consumables, such as helium, or power-hungry mechanical cryo-coolers. Infrared instruments that retain their performance at higher temperatures, where compact, single-stage thermoelectric coolers are effective, would offer significant benefits for space missions. Construction would be simpler, size, weight and power would be lower, and operation more long-lived and reliable.

Dark currents scale with the detector area, and an alternate approach to enhance the sensitivity is to reduce the area of the detector elements and use an array of micro lenses to concentrate the light onto the smaller active area of each pixel. As a result less cooling is required to achieve the desired sensitivity. However, optical concentrators based

on arrays of spherical micro lenses have proven challenging to fabricate resulting in unreliable performance.

A promising replacement technology involves a new class of lenses that are fabricated directly on the detector substrate using electron beam lithography and dry etching, essentially sculpting at the nanoscale. These are not traditional refractive lenses, but rather a series of rods at subwavelength diameters that modulate and focus the light. The result is a lens of less than 1/1000th of an inch in diameter, or about the size of a small speck of pollen, that can be fabricated over every pixel of the detector. Until recently, these were impossible to manufacture effectively, but the challenges have been overcome through a collaboration between JPL and Harvard.

Infrared imagers utilizing these nanostructured flat lenses offer great benefit to outer planet missions, as well as to small satellites conducting Earth observations, by reducing the size and complexity of the instruments.



Illustrated cross section of light passing through the nanostructured flat lenses.

**A NEW TECHNOLOGY UTILIZING NANOSTRUCTURED FLAT LENSES HAS THE POTENTIAL TO IMPROVE INFRARED SENSOR PERFORMANCE**

Opposite page: a microscopic image of a portion of an infrared detector array bonded to a readout integrated circuit. The enlarged inset shows a single nanostructured flat lens fabricated on the detector surface.



TH/27

# A SIDEWAYS GLANCE AT EARTH

When studying changes in the Earth's atmosphere, some of the most valuable data comes from measurements of its upper regions. However, these layers in our atmospheric blanket can also be the most difficult to observe.

Most earth observing satellites look downward and offer only a view of atmospheric layers that are stacked atop each other. But looking along the limb of the Earth, or sideways, allows atmospheric layers to be viewed separately.

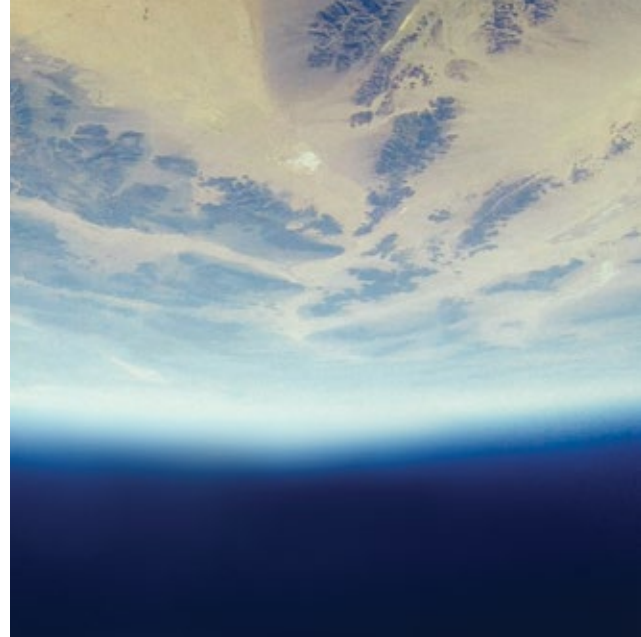
The Compact Adaptable Microwave Limb Sounder (CAMLs) is a microwave spectrometer that utilizes recent advancements in industrial Complementary Metal Oxide Semiconductor (CMOS) system-on-a-chip technology, capable of integrating a multitude of functions onto a single chip. A single CMOS chip can incorporate the high-speed analog-to-digital converter necessary for digitization, the high speed spectral processor, and an integrated frequency synthesizer, and provide 4000 channels with over 3 GHz bandwidth. The system-on-a-chip design approach enables extreme miniaturization of digital spectrometers. Additionally, the receiver front end consists of new indium phosphide low-noise amplifiers and mixers that span the 320 to 360 GHz spectral region.

CAMLs makes unique and essential observations of composition, humidity, temperature and clouds in Earth's troposphere and stratosphere, and builds on earlier external and JPL efforts with heritage from the Microwave Limb Sounder (MLS) instruments on NASA's UARS and Aura missions.

The implementation of digital spectrometers brings the advantage of high stability, critically important for long-term Earth observations. CAMLS also incorporates new, ultra-sensitive microwave receivers that make these essential observations using only a single receiver. The limb-sounding approach can provide near-global coverage with high vertical resolution, and at these frequencies the observations are unaffected by fine aerosols (such as those resulting from volcanic eruptions) and most clouds.

CAMLs also offers dramatic reductions in instrument complexity, mass, power requirements and size compared to previous microwave limb-viewing instruments. For example, while previous MLS instruments weighed almost 800 pounds (350 kg) and consumed 380 Watts, the CAMLS instrument package weighs just 44 pounds (20 kg) and draws a scanty 80 Watts—less than many incandescent lightbulbs.

CAMLs is scheduled to fly this year on a NASA aircraft for further testing and refinement, prior to possible deployment in orbit.



A NEW INSTRUMENT TO OBSERVE EARTH'S ATMOSPHERIC LAYERS MAKES USE OF CMOS TECHNOLOGY TO IMPROVE OUR UNDERSTANDING OF RAPID CLIMATE CHANGE WITH A SIGNIFICANT REDUCTION IN MASS AND POWER USE

Opposite page: a 48 Kelvin cold box contains the CAMLS receiver front end subsystem.

TH/28

# RAPPELLING OTHER WORLDS

Some of the most intriguing targets on planetary surfaces lie in hard-to-reach destinations. JPL has long led in the surface exploration of planetary bodies, and innovative rover designs will open new vistas on numerous moons and planets.

Tethered robots offer new options for navigating rugged terrain on other worlds. These machines can explore landscape features forbidden to traditional rovers. They can rappel down cliffs to investigate crater walls, escarpments and skylights, which could be entrances to lava tubes on the moon and Mars. Strata in Martian escarpments may reveal frozen water deposits. Recurring Slope Linea, or RSLs, have been observed on crater walls and other steep terrains. These dark seasonal streaks, which may involve water, appear then fade and reappear. All these features are of key interest in planetary exploration, and could be accessed with a new rover called Axel.

JPL and Caltech have been developing modular Axel rappelling rovers to access coveted, hard-to-reach science targets. These machines feature a two-wheeled, tail-dragging rover that unwinds its own umbilical tether as it traverses away from its “mothership.” In addition to providing support for steep terrain rappelling, the tether also provides power and communication to the rover. The rover contains two instrument bays that host three to four science instruments each, and features turret-mounted configurations that do not require a robotic arm to deploy and acquire measurements. The

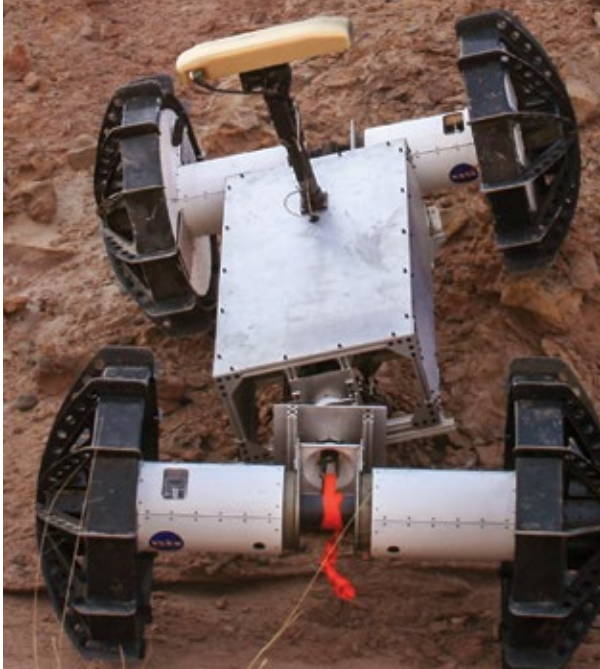
Axel rover can reposition its instruments and cameras while hanging from the tether on steep terrains, and can even operate while inverted.

The “mothership” could be a lander or a rover. In one rover configuration, called DuAxel, two Axels work in tandem to drive further than the range of a single, tethered unit; up to several miles. This will allow the investigation of craters, canyons and pits well beyond the range of a single tethered Axel. The DuAxel platform carries a module between the two Axels and can be placed on the ground as an anchor, allowing the combined unit to move its steep-climbing abilities to distant locations before deploying. This module sports a pan/tilt imaging mast to aid in DuAxel navigation and science observations along the way.

Axel technology enables access to and sampling of extreme terrains that could help unravel long-standing questions in planetary formation. DuAxel is intended for Mars exploration, with a potential focus on RSLs. The single Axel design might be used for a proposed lunar mission, called Moon Diver, that would investigate the sites of enormous, ancient lunar volcanic eruptions to understand their impact on the formation of planetary surfaces and atmospheres.

Opposite page: prototype Axel rover preparing to descend a cliffside. Right: a DuAxel rover.

EXPLORING OTHER PLANETS AND MOONS OFTEN REQUIRES NAVIGATING EXTREME AND DANGEROUS TERRAIN. NOVEL AND ROBUST ROVER DESIGNS ARE REVOLUTIONIZING HOW WE COULD EXPLORE THE HARSH SURFACES OF DISTANT WORLDS





TH/29

# GLIMPSES OF THE UNSEEN

Most of the radiation of the universe is emitted at submillimeter wavelengths, which are the most valuable wavelengths for understanding the complete stellar formation cycle as well as tracing the trail of water from interstellar clouds to solar system objects. New technology is enabling enhanced high-spectral resolution maps at these wavelengths.

Understanding how stars form and searching for water in the Solar System are best addressed by observations in the terahertz (THz) regime. Unfortunately, this spectral region between visible and microwave wavelengths is extremely challenging to observe. However, new JPL technology is enabling enhanced array receivers able to provide high-spectral resolution maps at these wavelengths. Heterodyne receivers consist of a source (local oscillator) and coherent detector (mixer). Efficient observations at these frequencies requires very powerful local oscillator arrays that generate a strong signal close to the frequency of the astronomical source.

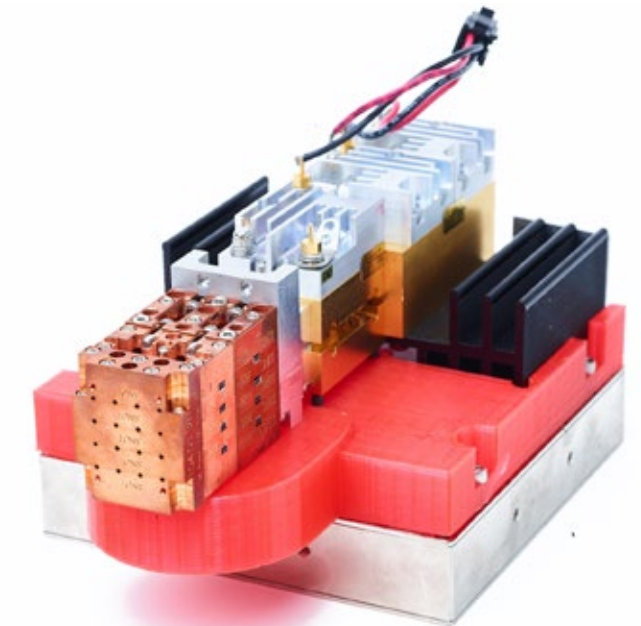
JPL is at the forefront in the development of very high-resolution array cameras at these frequencies. The newest generation of terahertz sources are much more efficient and offer more than ten-times increase in power while still operating at room temperature. This enables multi-pixel cameras while dramatically reducing the instrument mass and power consumption by an order of magnitude. In addition, the tuning bandwidth of these local oscillators has been increased from roughly 10 to 50 percent. A single receiver channel can now measure

a number of different important gas species, a task that previously required multiple receivers to accomplish. This is a tremendous breakthrough for future terahertz instruments.

This new array technology and increased sensitivity can dramatically improve astrophysical observations. For example, a 16-pixel 1.9 THz array has been demonstrated for carbon and oxygen observations that enables the mapping of a molecular cloud to be accomplished in hours instead of days. Another version is being developed for investigating water and other key species in comets and ocean worlds. Such a system will provide high-resolution maps within minutes, critical for studying rapidly rotating comets.

These components have been tested aboard NASA's Stratospheric Terahertz Observatory. A 64-pixel terahertz camera could soon be ready for deployment into balloon-borne, airborne and space astrophysical observatories to open new vistas in scientific inquiry. This technology is also baselined for the first-ever 183 GHz high-power cloud humidity radar that will fly on a NASA aircraft in 2019. This technology is also key for ultra-high data rate THz communications.

EXPLORING THE BIRTH  
OF NEW STARS IS ONE  
OF ASTRONOMY'S MOST  
COMPELLING QUESTS.  
TERAHERTZ COMPONENTS  
CAN NOW MAP STAR  
FORMING REGIONS AT  
UNPRECEDENTED SPEEDS



An ultra-compact 16-pixel 1.9-2.06 THz Local Oscillator source able to produce more than 30  $\mu$ W output power per pixel.



TH/30

# DUSTY SKIES

A next generation imaging spectrometer based on unique JPL technology will measure the interaction of light with airborne mineral molecules to answer key questions about the role of mineral dust in Earth's atmosphere.

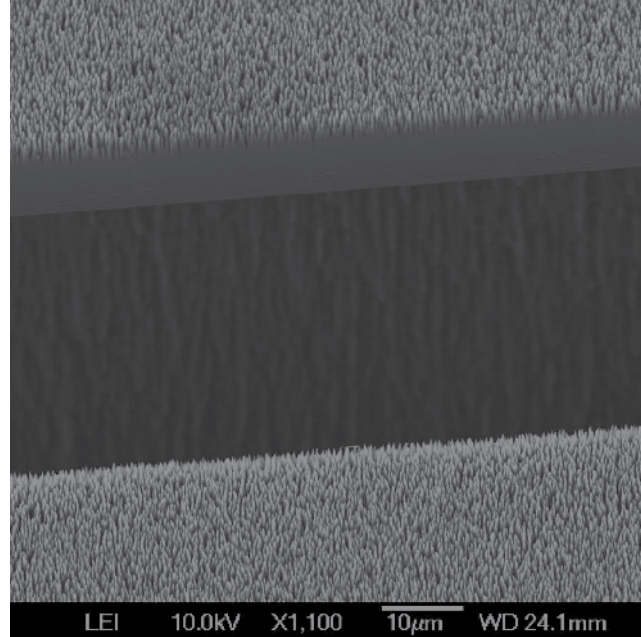
A key unknown for climatologists is how airborne mineral dust affects the temperature of the atmosphere. Different minerals have different physical, chemical, and optical properties that dictate their impact on weather and evolving climate.

A new experiment called the Earth Surface Mineral Dust Source Investigation (EMIT) has been selected by NASA to fly aboard the International Space Station that would make new, high accuracy measurements of the Earth's mineral dust source regions. These regions supply mineral dust aerosols to the atmosphere that influence energy balance, chemistry, and cloud formation. When dust settles, it fertilizes ocean and land ecosystems, melts snow, and can be a hazard on several levels. The details of these mineral dust interactions within the Earth system are uncertain and the EMIT measurements would be used to advance our understanding and predict future changes. EMIT can recognize different

minerals based on their specific spectral signatures.

The EMIT Concept incorporates a number of new technologies. E-beam fabricated blaze concave gratings enable the more compact Dyson imaging spectrometer design. An ultra-precise entrance slit is etched through a thin nitride membrane and integrated with state-of-the-art etched black silicon surfaces with its high light-trapping capability, to eliminate stray light in the instrument. In addition, the EMIT design includes a cryogenic detector array mount with six degrees of freedom, adjustable to sub-micron tolerances. The result is a Dyson spectrometer with optimum performance in terms of throughput and uniformity, and with a three-octave range covering from the visible to short-wavelength IR in 307 spectral channels

The EMIT imaging spectrometer approach is evolved from NASA's Moon Mineralogy Mapper that discovered water and hydroxyl compounds on the surface of the Moon in 2009.



MINERAL DUST IMPACTS THE ATMOSPHERE, OCEANS, TERRESTRIAL ECOSYSTEMS, CRYOSPHERE, AND INHABITED LANDS. NEW ADVANCES IN IMAGING SPECTROMETERS WILL PROVIDE INSIGHT INTO THE SOURCES AND TRANSPORT OF AIRBORNE DUST

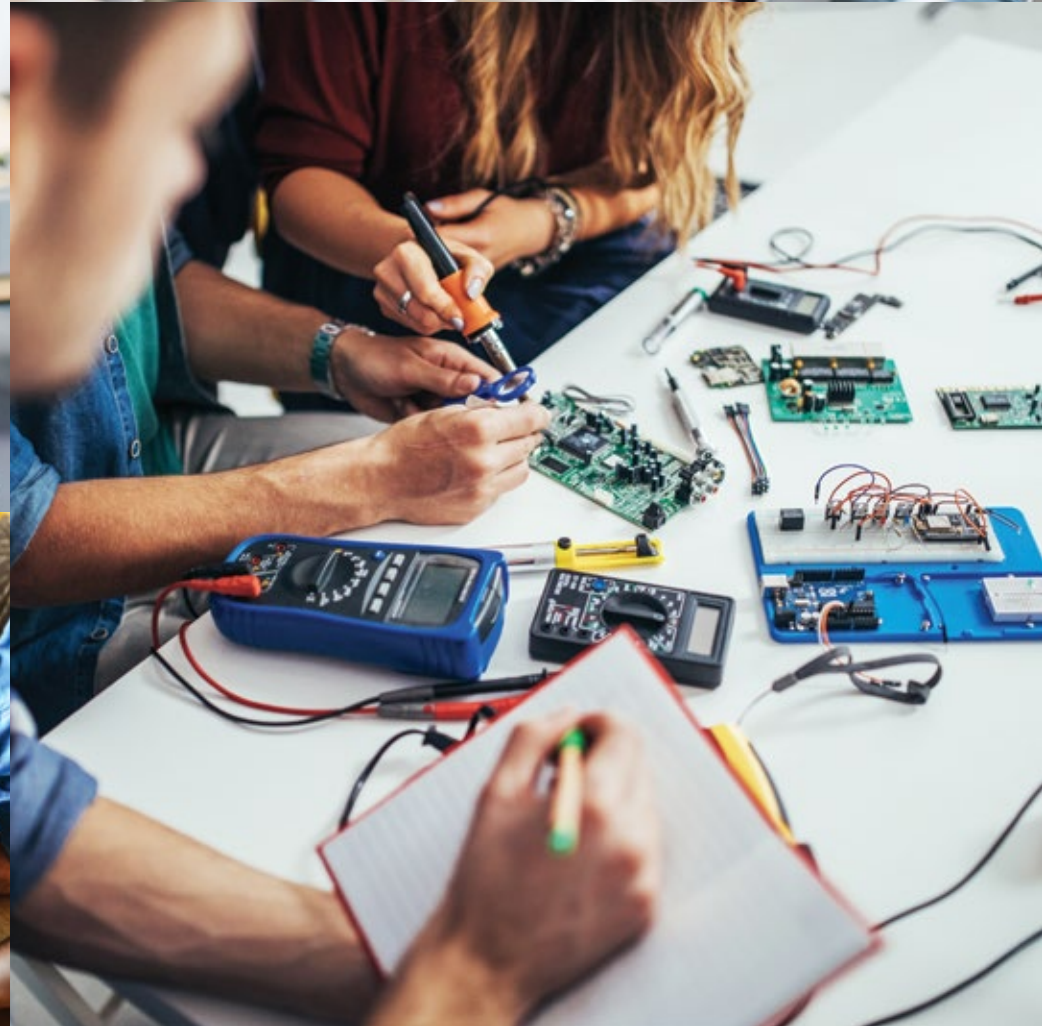


Opposite page: EMIT prototype high throughput three octave (380 to 2510 nm) imaging spectrometer. Top right: precision slit integrated with light-trapping black silicon. Lower right: E-beam fabricated blaze concave grating.

The information presented about EMIT is pre-decisional and is provided for planning and discussion purposes only.

TH/31

# BRIGHT SOURCING



Innovative ideas and new technologies are often left on hard drives or in the minds of the inventor for lack of time or support to investigate them. JPL's new crowdsourcing program seeks to bring these ideas into practical use.

Some of the nation's best young minds are searching for real-world problems to solve as part of their curriculum, senior projects, or capstones. JPL University Crowdsourcing kickstarts innovation by harnessing the energy and creativity of university students through crowdsourcing. Previous programs focused on local and regional interactions, but this new program allows institutions across the country to participate with a broader diversity of students than ever before. The result is an exponentially more powerful range of engagements and challenges explored.

University students seek real-world challenges to solve as part of their education. Through these crowdsourcing efforts they are exposed to such challenges, are coached by JPL engineers, are exposed to subject matter experts, and have opportunities to expand their horizons.

These innovative developments cover the full spectrum of space exploration, from new technologies, to IT solutions, and entire mission architectures. This not only provides

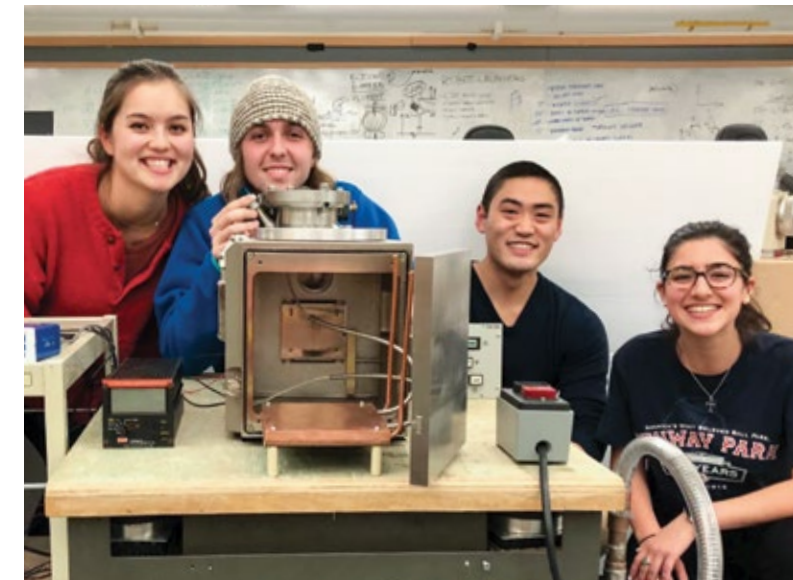
the space exploration community a source of innovative solutions to existing problems, but helps to develop and encourage the young minds so critical to the next decade—not just in spaceflight, but across the technological spectrum.

These crowdsourcing initiatives are focused on specific problems, with clearly defined goals. This is an outcomes-based project, which offers freedom to innovate.

JPL-sponsored pilot programs have explored a number of areas of technological development. Working with Northeastern University, the program supported the design, manufacture and testing of a prototype CubeSat self-inspection camera system designed to view the operation of deployable systems.

Ongoing projects include the design and testing of heat-rejection systems for CubeSats, self-folding spacecraft, and complex algorithms for additive manufacturing. Concepts for Europa sample return missions are also being pursued.

JPL IS REACHING OUT TO BRIGHT YOUNG MINDS ACROSS THE NATION TO ENCOURAGE AND SUPPORT NEW AND INNOVATIVE THINKING



Students from Northeastern University set up a thermal vacuum chamber to test a prototype CubeSat Self-Inspect Camera system.

CONTRIBUTOR  
PROFILES

**FRED Y. HADAEGH**

JPL Chief Technologist

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



**GREGORY L. DAVIS**

JPL Associate Chief Technologist

Dr. Davis holds a PhD from Rice University and an EMBA from Claremont Graduate University. Prior to his role as JPL Associate Chief Technologist, Dr. Davis worked as Division 35 Chief Technologist where he championed research and development across a broad spectrum of technologies, including advanced manufacturing, miniaturized electronics, and advanced modeling and simulation of complex systems.



**ASHLEY KARP (P. 10)**

Principal Investigator, Hybrid Rockets for CubeSat

Dr. Karp earned a PhD in Aeronautics and Astronautics from Stanford University. She is the propulsion lead for the Mars Ascent Vehicle study at JPL. Her research focuses on hybrid propulsion systems for challenging environmental conditions (e.g. Mars) and SmallSat applications.



**DOUGLAS HOFMANN (P. 6, 16.)**

Co-Investigator, Additive Manufacturing Lens, BMG

Dr. Hofmann received his PhD in Materials Science and Engineering from Caltech and his BS and MS in Mechanical Engineering from UC San Diego. He is the Principal Investigator of NASA's FAMIS Program (an ISS materials experiment) and leads research in bulk metallic glasses and metal 3D printing. He was the recipient of the Presidential Early Career Award for Scientists and Engineers from President Obama in 2012.



**EMILY LAW (P. 14)**

Principal Investigator, Solar System Treks Project (SSTP)

In addition to managing SSTP, Ms. Law also serves as the Data Systems and Technology Deputy Program Manager and the Planetary Data System Operations Manager. For over 20 years, she has provided leadership in the architecture, development, technology and operations of highly distributed data intensive systems for planetary and earth science.



**GARY BOLOTIN (P. 34)**

Principal Investigator, Compact Low Power Avionics for the Europa Lander Concept

Mr. Bolotin received a M.S. in Engineering from University of Illinois at Urban Champaign in 1985 and a B.S. in Engineering from Illinois Institute of Technology in 1984. He has been with JPL for more than 32 years. He is currently the lead of the Europa Lander Motor Controller. He has also managed engineering teams as both team leads and line manager at the section and group level.



**CHAOYIN ZHOU (P. 42)**

Principal Investigator, In Situ Oxygen Generation

Dr. Zhou received a PhD in Chemistry from Harvard specializing in molecular design and chemical synthesis, and has developed enabling materials for extreme environments. He is a materials and processes engineer and leads technology development for oxygen generation from CO<sub>2</sub> under benign conditions.



**CHRISTIAN ALBERT LINDENSMITH (P. 26)**

Principal Investigator, Digital Holographic Microscope

Dr. Lindensmith earned a B.S. in Physics from the University of Michigan and a Ph.D. in Physics at the University of Minnesota, studying superfluid helium. He has worked on a variety of missions and instruments, including the Planck cosmic microwave background mission, ChemCam (on MSL), the ground based Thirty Meter Telescope, and the James Webb Space Telescope. He has been involved in mission and instrument development for the search for extra-terrestrial life both inside and outside the solar system.



**DAN CRICHTON (P. 36)**

Principal Investigator and Program Manager, Data Science

Daniel Crichton is a program manager, principal investigator, and principal computer scientist. He is the leader of the Center for Data Science and Technology, a joint center formed with Caltech, focusing on the research, development and implementation of data intensive systems for science and missions. He leads the Data Science Program Office and serves as a principal investigator for multiple data science projects in planetary, earth science, and biomedicine.



**HARISH MANOHARA (P. 50)**

Technology Lead, Nanotechnology

Dr. Manohara received a PhD in Engineering Science from LSU. He led the Nano and Micro technology activities at JPL for more than ten years. His research interests include carbon nanotubes, vacuum microelectronics, extreme environment micro-sensors, and miniature instruments. He has developed miniature stereo camera, digital vacuum electronics, and field emission technologies.



**MICHAEL HECHT (P. 32)**

Principal Investigator Mars Oxygen ISRU Experiment (MOXIE)

Dr. Hecht's research is focused on Mars, with emphasis on polar processes, soil physics and chemistry, and the hydrological cycle. He was Principal Investigator of the MECA instrument suite on the Phoenix Lander in 2008, which notably discovered that perchlorate is the dominant form of chlorine in the Martian soil. Dr. Hecht is currently the Associate Director for Research Management at the MIT Haystack Observatory.



**IAN CLARK (P. 48)**

Principal Investigator, ASPIRE

Dr. Clark is a Systems Engineer in the EDL and Advanced Technologies Group and currently serves as the PI for the ASPIRE test activity. His primary activities are in the area of Entry Descent and Landing (EDL) and he has previously served as the PI of the Low-Density Supersonic Decelerators Project.



## CONTRIBUTOR PROFILES

(continued)

### JAMES SMITH (P. 66)

Principal Investigator, JPL University Crowdsourcing Initiative

Mr. Smith is a Supervisor and the DHFR Antenna Mechanical Systems Engineer. Known for people leadership and capability development, he authored NASA's first Programmatic Environmental Assessment, was instrumental in capturing multiple missions, most recently SMAP and CAL; is a co-inventor on multiple technologies, and originated the JPL Innovation Jam.



### ERIC JONG-OOK SUH (P. 30)

Principal Investigator, Post-Irradiation Recovery Solution for Electronic Parts

Dr. Suh is a technologist in the Electronic Packaging Technology Development group. He received a PhD in Materials Science and Engineering from University of California, Los Angeles. He has researched behavior of electronic packaging materials at extreme environments and additive manufacturing of gradient alloys.



### JOSE V. SILES (P. 62)

Principal Investigator, Multi-Pixel Terahertz LO Sources

Dr. Siles led the LO system of NASA's Stratospheric THz Observatory (flown in 2016/2017). His research interests include the development of submillimeter-wave array local oscillator and receivers. He is PI of several NASA funded programs to develop high-power Terahertz LO sources and array receivers for high-spectral resolution mapping of star-forming regions, comets and water in ocean worlds.



### PATRICK MORRISSEY (P. 22)

Principal Investigator, KCWI

Dr. Morrissey was Principal Research Scientist at Caltech and co-investigator for the GALEX UV Explorer mission, which surveyed the sky from 2003-2013. He was KCWI Project Scientist and optical designer, and is now the lead for the photon counting cameras of the WFIRST coronagraph.



### SVETLA HRISTOVA-VELEVA (P. 20)

Principal Investigator, North Atlantic Hurricane Watch Portal

Dr. Hristova-Veleva's recent work has been the development of retrieval algorithms for estimation of a variety of geophysical parameters using the passive microwave observations of the AMSR instrument on the ADEOS-II spacecraft. She worked on modeling of precipitation systems and their remotely-sensed characteristics in support of studies related to the design of future scatterometers.



### RICHARD DOYLE (P. 24)

Principal Investigator, High Performance Space Computer

Dr. Doyle is the Program Manager for Information and Data Science at JPL. His activities and interests span data science, autonomous systems, computing systems, software engineering, space asset protection, and related topics that apply computer and data science principles and capabilities to space missions.



### ANDREW JOHNSON (P. 18)

Principal Investigator, Terrain Relative Navigation — M2020

Dr. Johnson received a PhD in Robotics from Carnegie Mellon University before joining JPL where he and his team are developing real-time autonomous navigation and mapping technologies for Entry Descent and Landing. Their current project is the Lander Vision System, a terrain relative navigation sensor for the Mars 2020 mission.



### SABAH BUX (P. 8)

Principal Investigator, Advanced Radiation Shielding

Dr. Bux received her PhD in inorganic chemistry from UCLA. She is a technologist in the thermal energy research and advancement group (3464) where she is a lead researcher. Her main research focus is the investigation of new materials using novel techniques/processes.



### MORY GHARIB (P. 54)

Caltech Director, CAST

Professor Gharib is the Director of the Graduate Aerospace Laboratories at Caltech and the Center for Autonomous Systems and Technologies. His research interests in conventional fluid dynamics include vortex dynamics, active and passive flow control, micro fluid dynamics, as well as advanced flow-imaging diagnostics.



### RICHARD HODGES (P. 6, 44, 46)

Principal Investigator, Additive Manufacturing Lens and ISARA Mission, MarCO Antenna. Co-Investigator, KaTENna Mesh Reflector

Dr. Hodges received the PhD in Electrical Engineering from University of California, Los Angeles. He is a JPL Principal Engineer, Senior Member of the IEEE and Technical Group Supervisor of the Spacecraft Antennas Group, which develops spacecraft telecom and instrument antennas for JPL missions. His current research focus is on antenna technology for spacecraft applications.



### ROBERT O. GREEN (P. 64)

Principal Investigator, Earth Venture EMIT

Dr. Green is a science co-investigator on the CRISM imaging spectrometer for Mars, Instrument Scientist for the M3 imaging spectrometer on Chandrayaan-1, MISE imaging spectrometer for Europa and Experiment Scientist for the NASA AVIRIS airborne imaging spectrometer. His research interests include imaging spectroscopy with a focus on advanced instrumentation, model-based spectroscopic inversions, and measurement calibration and validation.



### ROBERT PETER DILLON (P. 16)

Principal Investigator, Bulk Metallic Glass Gears

Dr. Dillon is a technologist in the Materials Development and Manufacturing Technology Group at JPL. He received a PhD in materials science and engineering from UC Irvine. His research interests include additive manufacturing of metal alloys and gradients and materials and processes for extreme environment capable spacecraft electronics and mechanisms.



## CONTRIBUTOR PROFILES

(continued)

### NATHANIEL LIVESEY (P. 58)

Principal Investigator, CAMLS

Dr. Livesey is the Principal Investigator for the Microwave Limb Sounder instrument on NASA's Aura Earth atmospheric science mission. His research interests include the development and application of microwave remote sounding instruments, and the data processing algorithms associated with converting remote radiance measurements into geophysical profiles.



### SOON-JO CHUNG (P. 54)

Caltech Lead investigator, JPL-CAST Autonomy

Dr. Chung is an Associate Professor of Aerospace and Bren Scholar and JPL Research Scientist. He received a PhD in estimation and control from MIT. Prof. Chung's research focuses on distributed spacecraft systems, space autonomous systems, and aerospace robotics, and in particular, on the theory and application of complex nonlinear dynamics, control, estimation, guidance, and navigation of autonomous space and air vehicles.



### YAHYA RAHMAT-SAMII (P. 46, 6)

Principal Investigator, KaTENna Mesh Reflector.  
Co-investigator, Additive Manufacturing Lens

Prof. Rahmat-Samii obtained his PhD from University of Illinois, Urbana-Champaign. He is a member of the US National Academy of Engineering and a Fellow of five societies including IEEE and URSI. He is a co-author of five books and over 1000 journal and conference papers. He is the recipient of numerous awards including the IEEE Electromagnetics Field Medal. His research interests cover wide spectrum of antenna designs from medical to space applications and the nature based optimization techniques.



### LUTHER BEEGLE (P. 38)

Principal Investigator, SHERLOC

Dr. BeeGLE received a PhD in Physics from the University of Alabama at Birmingham. His research interests include the in situ search for evidence of life on planetary bodies in the solar system and the potential for sample acquisition, handling & processing hardware to alter scientific results on robotic missions. He is a Surface Sampling System Scientist on Mars Science Laboratory supporting drilling and arm activities on Mars.



### AMIR RAHMANI (P. 52)

Principal Investigator, Swarm Autonomy

Dr. Rahmani has a Ph.D. from University of Washington and was an assistant professor at the University of Miami prior to joining JPL. He has over a decade research experience in distributed space systems, formation flying, as well as swarm robotics. He is the NASA STTR subtopic manager on coordination and control of swarm of space vehicles.



### KEITH CHIN (P. 40)

Principal Investigator, High Power Energy Storage for Deep Space Smallsat Applications

Dr. Chin holds BS, MS and PhD degrees in chemical engineering. As a technologist, his primary goal is to develop innovative electrochemical technologies to enable new and challenging autonomous spacecraft missions. His research focuses on energy storage, energy generation, and in-situ electrochemical instrumentation. He supported numerous flight projects as a battery, power subsystem engineer, software developer and/or systems engineer.



### ABIGAIL ALLWOOD (P. 12)

Principal Investigator, PIXL or Planetary Instrument for X-ray Lithochemistry

Dr. Allwood is a field geologist and an astrobiologist with a strong interest in the early Earth, microbial sediments, evaporites and the oldest record of life on Earth. Abby is the first female principal investigator on a Mars mission and earned her Ph.D. in Earth Science, Macquarie University, Sydney, Australia (2006) and her B. App. Sc., Queensland University of Technology, Brisbane, Australia (2002).



### ALEX SOIBEL (P. 56)

Principal Investigator, Mid-Wave IR Detectors with Optical Concentrators

Dr. A. Soibel, is Senior Member of Engineering Staff in JPL, NASA/Caltech where he works on the development of detectors and mid-IR lasers. He has extensive experience in design, fabrication and testing of III-V semiconductor detectors and lasers. He has co-authored more than 50 refereed articles, four book chapter and 8 patents.



### ISSA NESNAS (P. 60)

Principal Investigator, Axel Rover System

Dr. Nesnas is a principal technologist and supervisor of the Robotic Mobility group at JPL. He leads research in robotics to explore extreme planetary terrains and microgravity bodies and supports flight projects including the development of autonomous rover navigation and visual target tracking for Curiosity and future Mars 2020 rovers. He holds a B.E. degree in Electrical Engineering from Manhattan College and a M.S. and Ph.D. in Mechanical Engineering with a specialization in robotics from the University of Notre Dame..



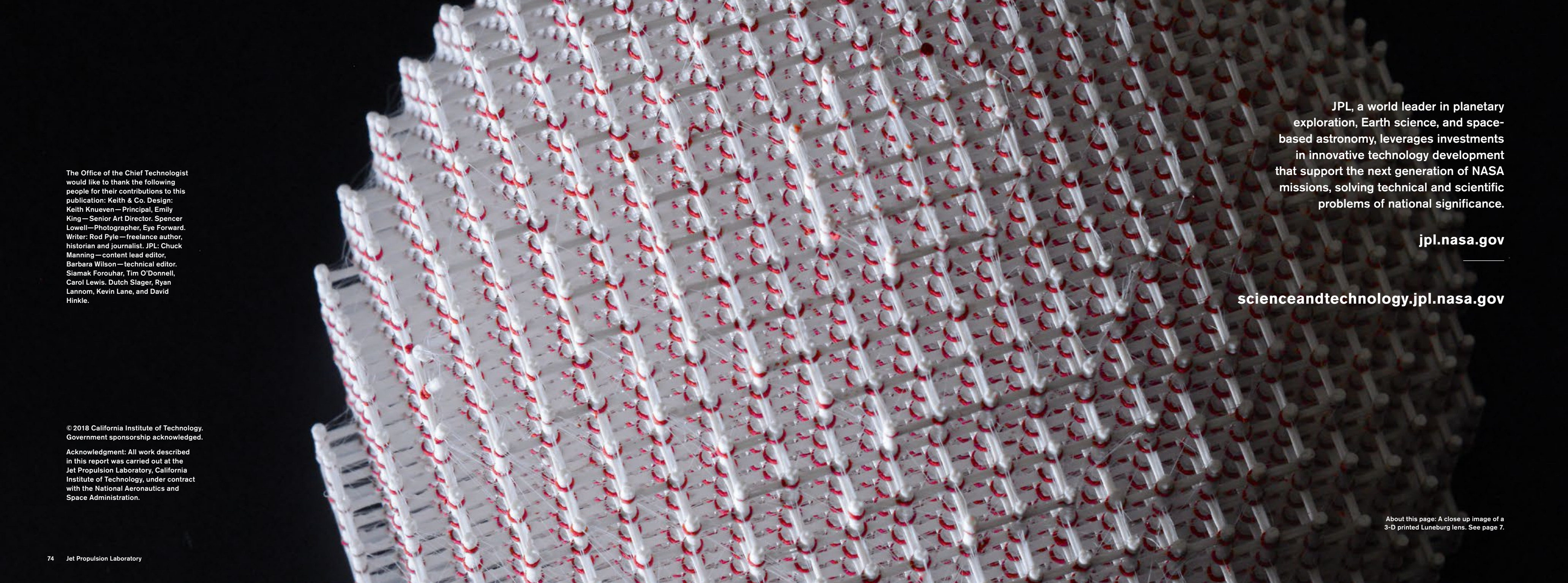
### ANDREW KLESH (P. 28)

Principal Investigator, Glacial Moulin Mapping Using Robotic Submersible

Dr. Klesh received a PhD in Aerospace Engineering from the University of Michigan. He is chief engineer for the MarCO CubeSat mission to Mars, and technical lead for the Buoyant Rover for Under Ice Exploration. His research interests span under-ice environments to deep space exploration.



Credit: Andrew Hara and Heek Observatory



The Office of the Chief Technologist would like to thank the following people for their contributions to this publication: Keith & Co. Design: Keith Knueven—Principal, Emily King—Senior Art Director. Spencer Lowell—Photographer, Eye Forward. Writer: Rod Pyle—freelance author, historian and journalist. JPL: Chuck Manning—content lead editor, Barbara Wilson—technical editor. Siamak Forouhar, Tim O'Donnell, Carol Lewis, Dutch Slager, Ryan Lannom, Kevin Lane, and David Hinkle.

© 2018 California Institute of Technology. Government sponsorship acknowledged.

Acknowledgment: All work described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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

[jpl.nasa.gov](http://jpl.nasa.gov)

[scienceandtechnology.jpl.nasa.gov](http://scienceandtechnology.jpl.nasa.gov)

About this page: A close up image of a 3-D printed Luneburg lens. See page 7.



National Aeronautics and Space Administration

**Jet Propulsion Laboratory**  
California Institute of Technology  
Pasadena, California

[www.jpl.nasa.gov](http://www.jpl.nasa.gov)

CL#18-4304  
JPL 400-1688 08/18