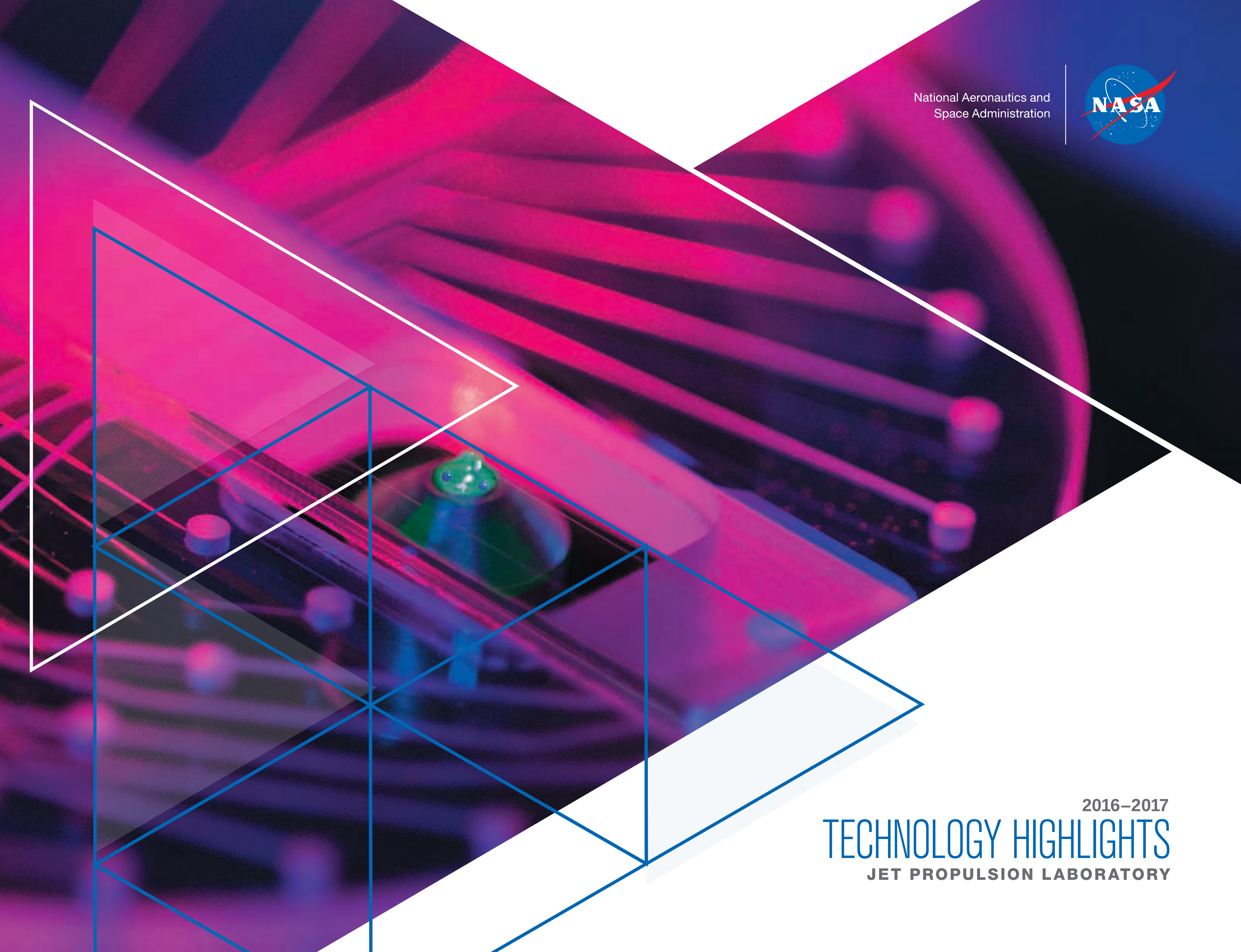


National Aeronautics and
Space Administration

2016–2017

# TECHNOLOGY HIGHLIGHTS

JET PROPULSION LABORATORY

# OFFICE OF THE DIRECTOR

AT JPL, WE ARE PROUD OF OUR MISSION AS NASA'S LEAD CENTER FOR THE ROBOTIC EXPLORATION OF SPACE. WE DESIGN, BUILD, LAUNCH, AND OPERATE SPACECRAFT, SOME OF WHICH HAVE TRAVELED TO THE OUTER REACHES OF THE SOLAR SYSTEM AND SURVIVED NEARLY FOUR DECADES IN THE DEEP-SPACE ENVIRONMENT. OUR SUCCESSES INCLUDE LANDING AND OPERATING ROVERS ON MARS, TRACKING RECEDING GLACIERS AND LOSS OF GROUND WATER ON EARTH, AND DISCOVERING A HOST OF EARTH-LIKE PLANETS ACROSS THE MILKY WAY. WE OWE ALL THESE DISCOVERIES TO THE CREATIVE VISION AND INGENUITY OF JPLERS, WHO HAVE ALWAYS HAD A GIFT FOR TRANSFORMING TODAY'S TECHNOLOGY INTO TOMORROW'S MISSIONS OF DISCOVERY.

This creativity dates to the origins of JPL, when technologists fascinated by the potential of rocket propulsion carried out their experiments in an arroyo a few miles from Caltech. That creative drive remains a key part of JPL culture to this day, as we endeavor to transform 21st-century technologies into unique and exciting new missions.

In the pages that follow, you will find descriptions of technologies that we believe show particular promise for future exploration. Some JPLers dream about intelligent rovers on Mars making real-time decisions to optimize the mission outcomes in the face of unpredictable challenges, and bringing samples of the Red Planet back to Earth. Others envision small explorers that can be transported flat and "pop up" origami-style when released on the surface to make discoveries in areas that are otherwise too dangerous or inaccessible.

Roboticists envision modular autonomous systems to enable in-space construction of telescopes with unprecedented dimensions to peer into the far reaches of the universe. Computer scientists explore new ways to extract unexpected deep-space events from the vast volumes of data returned by the array of radio telescopes constantly monitoring the skies.

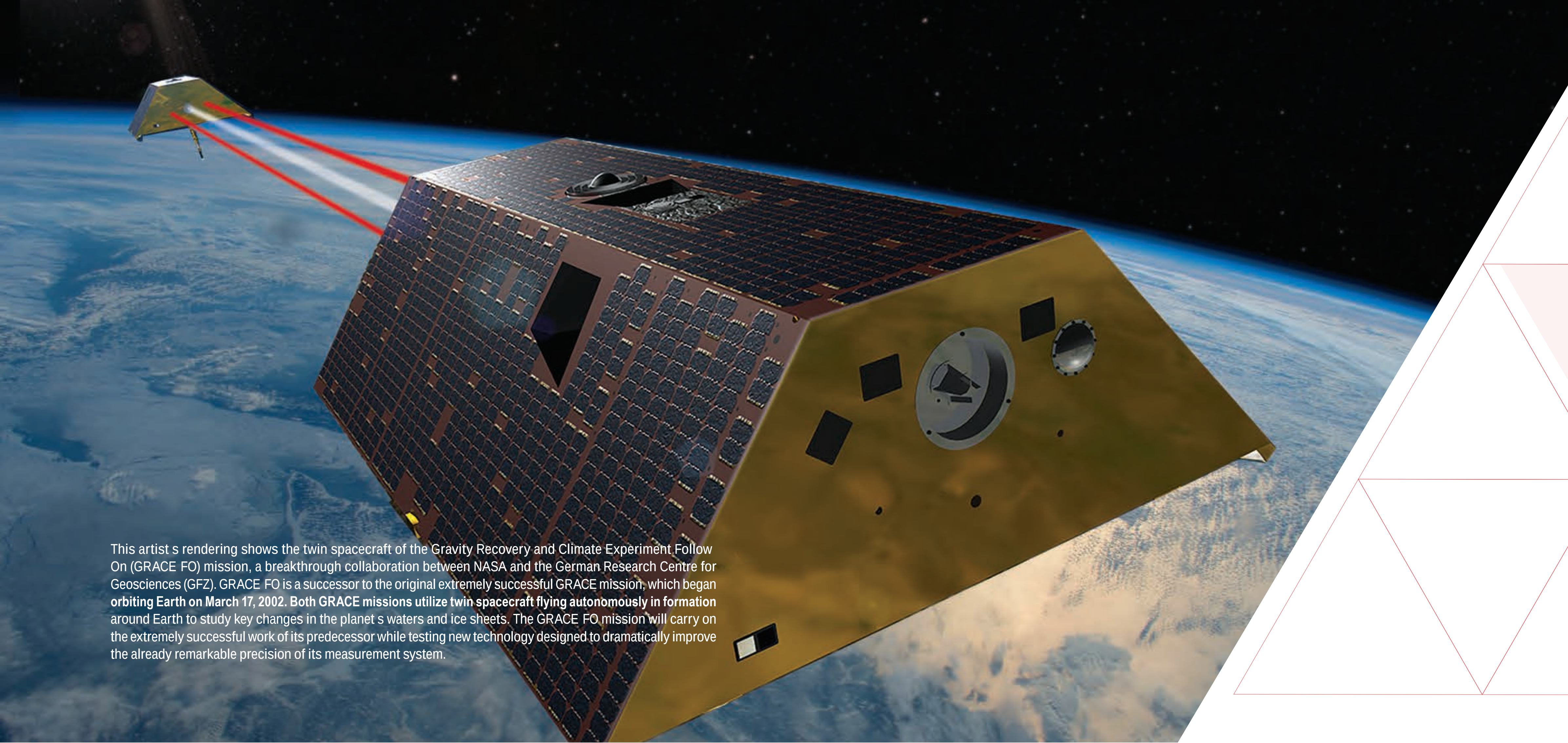
And for issues closer to home, instrument pioneers develop new approaches to probe ever deeper into the delicate interdependence among the dynamics of greenhouse gas profiles, winds, ocean currents, and melting snow fields and glaciers to inform models of Earth's climate necessary to understand the evolution and future sustainability of our Green Planet.

I welcome you to this new edition of JPL Technology Highlights, invite you to explore its pages, and invite you to share our creative vision for the exploration of space.

Michael Watkins | **JPL Director**

# OFFICE OF THE CHIEF TECHNOLOGIST

Understanding the behavior of water, the most precious resource on Earth, may be the most important single achievement of the 21st century, and JPL is at the forefront of efforts to unravel these secrets. For over 15 years, the Gravity Recovery and Climate Experiment (GRACE) has revolutionized our knowledge of Earth's water cycle, provided insight into the distribution of water and ice, seen clear trends in ice-mass loss in the Arctic and Antarctic, and provided a new understanding of drought and groundwater loss worldwide. Scientific and technological innovation is fundamental to the success of missions such as GRACE. The Office of the Chief Technologist provides for the development of innovative and strategic technologies at JPL that support the next generation of missions and research activities across the Laboratory.



This artist s rendering shows the twin spacecraft of the Gravity Recovery and Climate Experiment Follow On (GRACE FO) mission, a breakthrough collaboration between NASA and the German Research Centre for Geosciences (GFZ). GRACE FO is a successor to the original extremely successful GRACE mission, which began **orbiting Earth on March 17, 2002. Both GRACE missions utilize twin spacecraft flying autonomously in formation** around Earth to study key changes in the planet s waters and ice sheets. The GRACE FO mission will carry on the extremely successful work of its predecessor while testing new technology designed to dramatically improve the already remarkable precision of its measurement system.

IN AN AGE OF PROLIFERATING TECHNOLOGIES, OUR CHALLENGE AT JPL BECOMES TO INNOVATE AND LEVERAGE THE RIGHT ONES FOR THE UNIQUE CHALLENGES OF SPACE EXPLORATION. FOR MANY, THE TERM "TECHNOLOGY" EVOKES IMAGES RANGING FROM SMARTPHONES, TO NEXT-GENERATION ELECTRIC CARS, TO AUTONOMOUS AERIAL PODS FOR INDIVIDUAL TRANSPORTATION. IN OUR JPL COMMUNITY, TECHNOLOGY CARRIES A SPECIFIC MEANING: THE MEANS TO ENABLE EXCITING NEW MISSIONS.

We have made advances in engineering at the nanoscale to develop sensitive new particle detectors capable of determining the direction of the source, to extend sensitive CCD imaging arrays to operate in the ultraviolet and X-ray, to increase the operating temperature of detectors in the infrared, and to generate new approaches to block the light from a distant star and observe the faint exoplanets circling nearby. In the field of superconductivity, the difficulty of sustaining the superconducting state in the presence of weak electromagnetic disturbances has been transformed into an ultrasensitive detector. And superconductor quantum locking has been incorporated into a novel design simplifying a rendezvous in space, such as with the capture of a cached sample that has been launched into Mars orbit for return to Earth.

JPL has achieved many new capabilities by leveraging technologies that have seen rapid advances for commercial applications. For example, the advantages of rapid 3-D printing have been pushed to an additional fourth "dimension," namely by constructing space systems whose functions evolve over the course of the mission. And the vast diversity of rapidly advancing commercial electronics has been leveraged in many ways, including miniature chemical analyzers and radar imagers for use on Earth as well as distant space targets.

Other breakthroughs that will ensure more exciting and productive missions in the future include advances in Li-ion batteries for cold environments, increased lifetimes for ion engines taking missions to ever more challenging targets, and resilient rover wheels for long-duration rovers on Mars. A novel approach using magnetic fields allows precision tracking in areas where radio tracking breaks down, such as for locating rovers in rugged or underground terrain, or first responders helping victims of a disaster in an urban environment.

The following pages show that the technological opportunities at JPL have never been greater. Our primary challenge is to seize these opportunities and to take these ideas to practice, while finding ways to manage the attendant complexity and risk. We will embrace this bright future—just as JPL always has—and I welcome you to the 2016–2017 edition of our Technology Highlights publication.

Fred Hadaegh | **JPL Chief Technologist**

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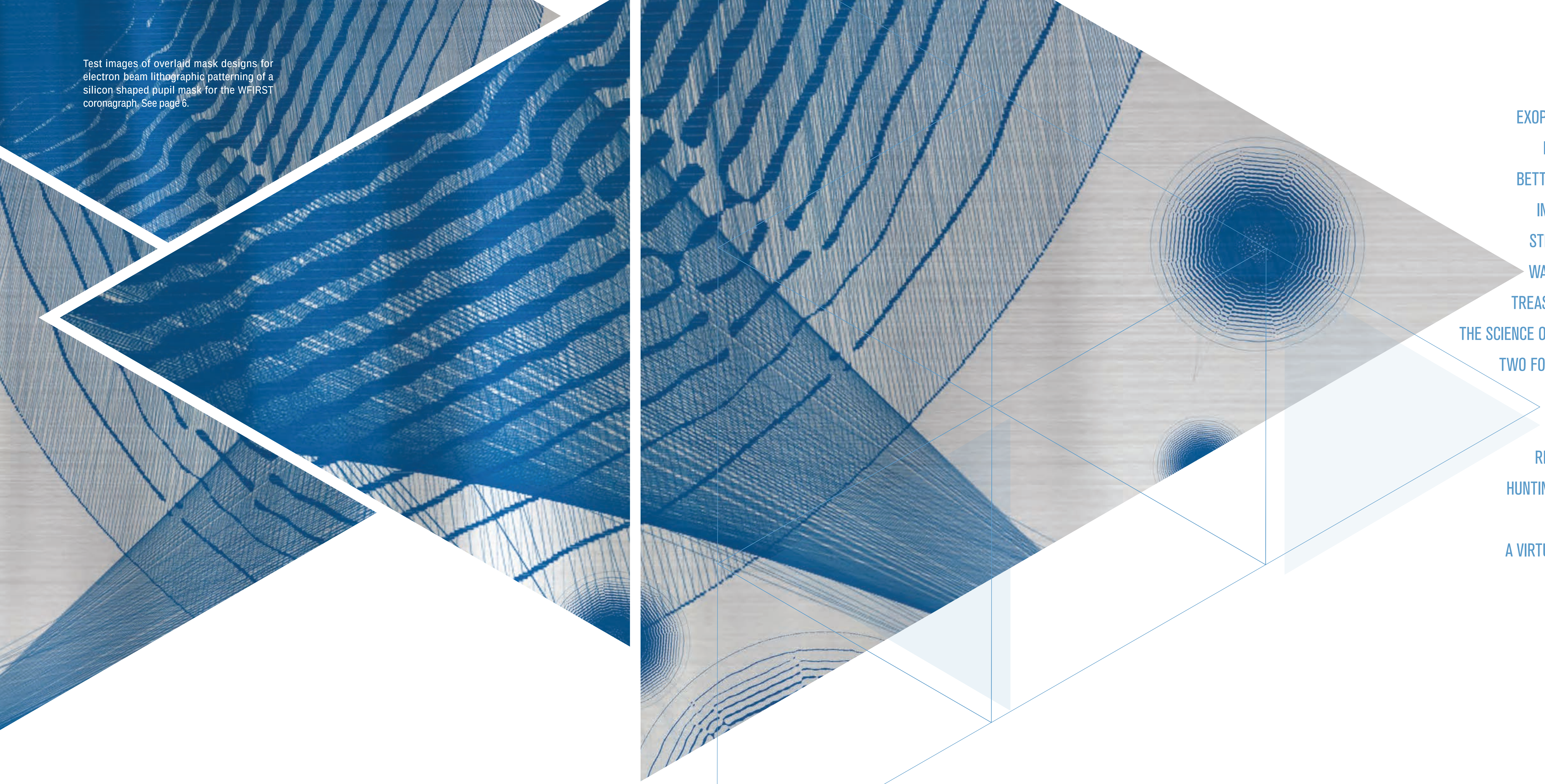


Test images of overlaid mask designs for electron beam lithographic patterning of a silicon shaped pupil mask for the WFIRST coronagraph. See page 6.

# EXOPLANETARY FIRST LIGHT

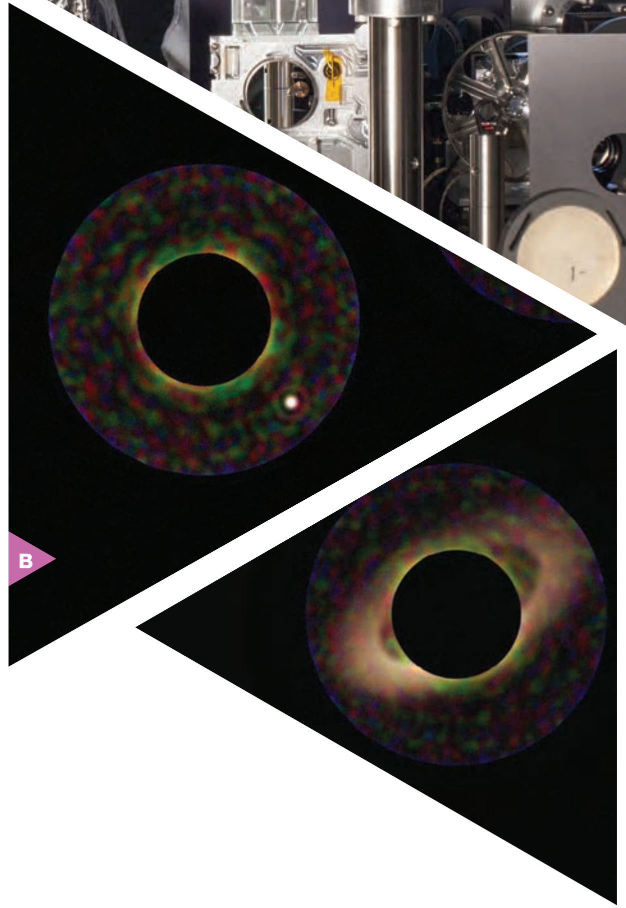
THE VAST MAJORITY OF EXOPLANETS HAVE BEEN DETECTED INDIRECTLY BY MEASURING THE GRAVITATIONAL TUG ON THEIR HOST STARS, OR BY SENSING THE DIP IN BRIGHTNESS OF THAT STAR AS A PLANET TRANSITS ACROSS OUR LINE OF SIGHT. WFIRST, THE WIDE-FIELD INFRARED SURVEY TELESCOPE, IS THE FIRST NASA SPACE TELESCOPE DESIGNED TO DIRECTLY IMAGE AND CHARACTERIZE EXOPLANETS, AS WELL AS DEBRIS DISKS IN OTHER STAR SYSTEMS THAT ARE POTENTIAL PLANETARY BIRTHPLACES.

WFIRST WOULD INCLUDE the first high-contrast stellar coronagraph instrument ever flown, utilizing optical components created at JPL and Princeton University to directly image large exoplanets from reflected light. The telescope would also be capable of performing spectroscopy on exoplanet atmospheres, especially super-Earths, planets much like our own except larger. This would aid in identifying whether these large terrestrial worlds might be capable of supporting life.

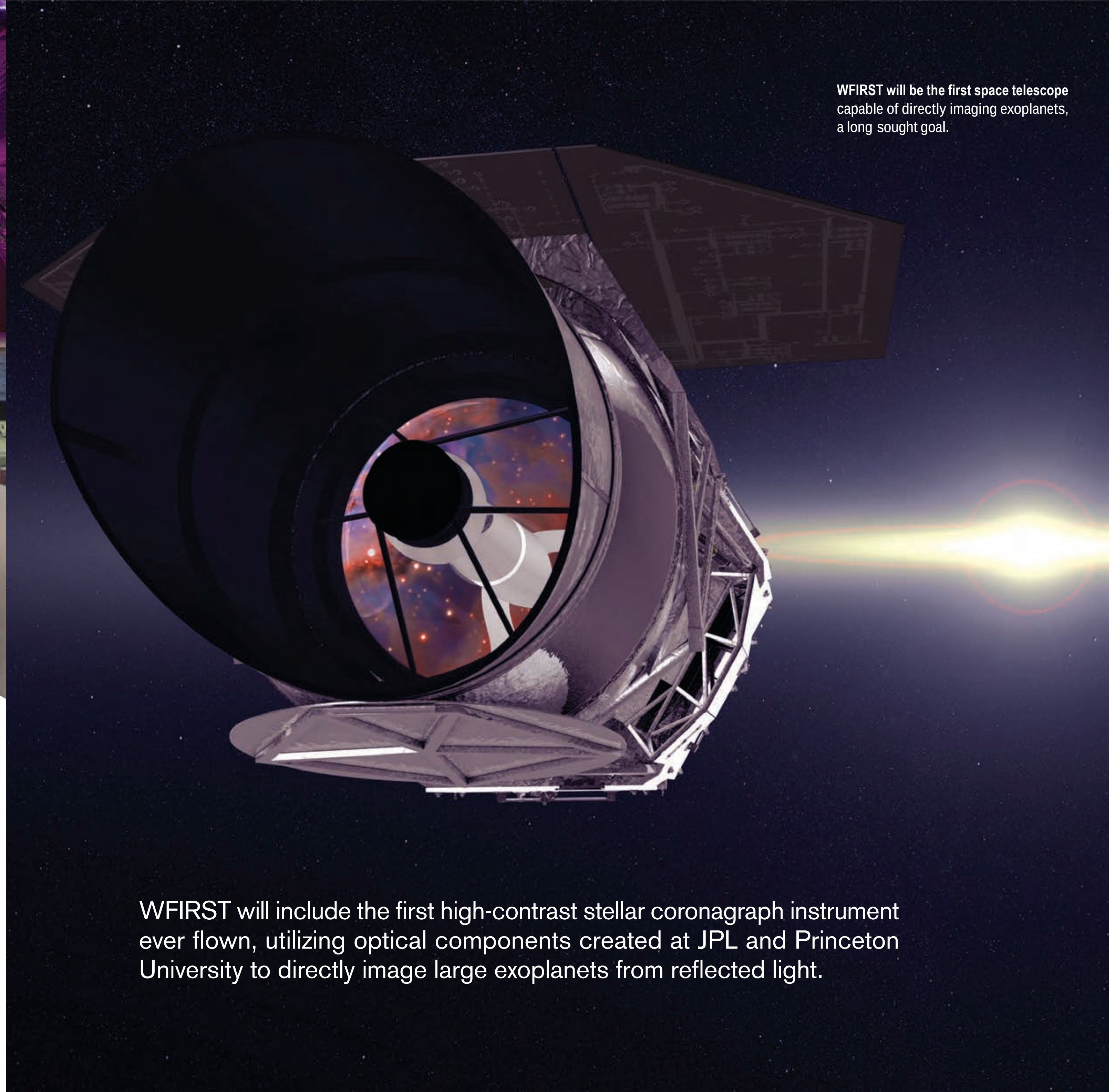
WFIRST's complex optical train uses two types of coronagraphs, a Hybrid-Lyot Coronagraph (HLC), designed and built at JPL, and a Shaped Pupil Coronagraph (SPC) designed by Princeton University. JPL's Microdevices Laboratory (MDL) is fabricating the masks for both. MDL is one of the few facilities in the world capable of creating these ultra-accurate optical components, which require grayscale lithography with nanometer-scale accuracy. The SPC uses a pupil-plane reflective mask that has ultra-dark regions of plasma-etched "black silicon" light-absorbing optics, also fabricated and patterned using electron-beam lithography.

These masks work in conjunction with the rest of the coronagraph's optics to suppress the light of a star by nine orders of magnitude (one billion times) to enable direct imaging of the star's orbiting planets. Diffraction and optical error must be minimized at each step of the process, despite the numerous folds, bends, and other optical manipulations in the telescope's light path.

To fine-tune the final image, a deformable mirror, designed by JPL and built by Xinetics, a division of Northrop Grumman, is inserted in the light path. This optic uses ultra-thin reflective glass with tiny mechanical actuators behind it—more than 2000 of them for a single 48-square-millimeter mirror that is smaller than a postage stamp—to precisely control the wavefront. Minute errors detected in the star's image are converted into signals for these actuators, which then flex and distort the mirror to create tiny corrections—a change of less than the size of a single atom. This correction, combined with the tight manufacturing tolerances of the optical train, suppresses the bright light of the host star to create a nearly perfect image. WFIRST will seek to answer questions about large exoplanets and their environments in unparalleled detail.

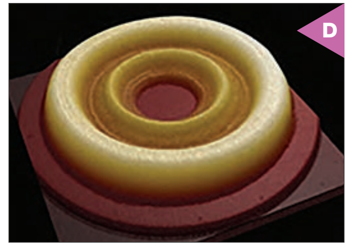


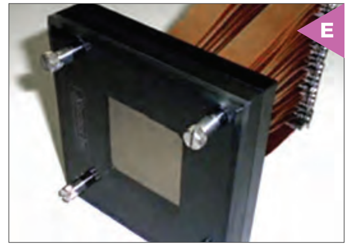
A• A vacuum chamber is used for testing WFIRST and other coronagraphs. A star is simulated inside the chamber using light brought in by an optical fiber, and the light of this "star" is suppressed in the testbed by coronagraph masks and deformable mirrors. B•Simulation of expected image of a planet with no zodiacal dust cloud (top) and with a zodiacal dust cloud (bottom).

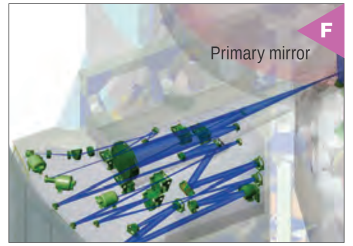


**WFIRST will be the first space telescope** capable of directly imaging exoplanets, a long sought goal.

WFIRST will include the first high-contrast stellar coronagraph instrument ever flown, utilizing optical components created at JPL and Princeton University to directly image large exoplanets from reflected light.







C• A black silicon mask suppresses illumination from the host star to reveal light from an orbiting exoplanet that is up to a billion times fainter. D• An Atomic Force Microscope surface profile image of an e-beam-fabricated HLC occulting mask. E• Deformable mirror system, designed at JPL and built by Xynetics, provides sub-nanometer-scale corrections to flexible mirrors. F• WFIRST's coronagraphs are part of a long chain of optics, some 22 reflective surfaces, that can be configured into 2000 different combinations.

# FIRST LINE OF DEFENSE

JPL's solid state neutron detector (SSND) element is smaller than a dime.

RADIATION, WHETHER IN SPACE OR ON EARTH, CAN BE HAZARDOUS FOR LIVING ORGANISMS. ONGOING RESEARCH AT JPL HAS RESULTED IN IMPROVED AND SMALLER NEUTRON DETECTORS, WHICH WILL HAVE MANY APPLICATIONS IN SPACEFLIGHT, SERVING AS “CANARIES-IN-THE-MINE” TO MEASURE RADIATION IN DEEP-SPACE ENVIRONMENTS BEFORE PUTTING HUMANS AT RISK.

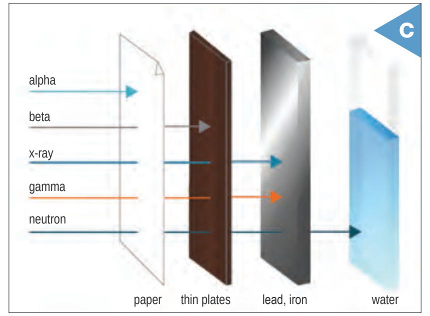
SUCH DETECTORS ARE IMPORTANT ON EARTH AS WELL. Detecting radiation from concealed nuclear threats has become a primary concern since the attacks of September 11, 2001. Neutrons are a highly specific indicator of fissile material, the illegal importing of which poses serious national security concerns. Neutrons are extremely difficult to detect, as they are uncharged and experience no repulsion as they pass through matter, so improvements in detector sensitivity are important.

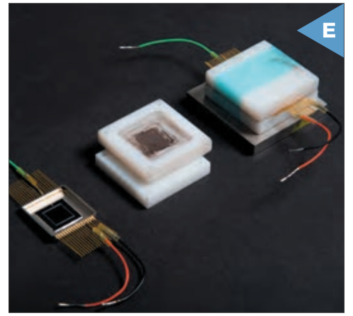
Currently available detectors use tubes filled with helium-3 at high pressure. They are becoming increasingly expensive due to dwindling helium-3 gas supplies, require high voltages and high pressures, and are unable to discern the directionality of the source. A compact, scalable, less expensive, low-power-consumption handheld or remotely usable unit (mountable on an aerial drone for mobility, for example) will transform neutron detection.

JPL is optimizing ultra-thin silicon detector technology first developed at the University of California at Berkeley. This solid-state neutron detector (SSND) uses boron-10 layers to convert neutrons into alpha particles, which can then be accurately measured. These layers are stacked—multiple detection layers can pinpoint the direction of the neutron emission source by tracking the course of the particle across multiple surfaces. Stacking also increases sensitivity.

These detectors can be fit into small handheld units, emplaced on aerial drones, or mounted at fixed locations. Their low power requirements—they use small batteries—support this flexibility of use and movement. These improved neutron detectors have been successfully field tested in maritime port conditions and are able to identify radioactive materials through cargo container walls and other challenging conditions. Their smaller size and greatly reduced cost will result in wider applications in national security and the characterization of radiation threats in deep-space environments.

**A·** Improved, lightweight neutron detectors will enable assessment of space environments before exposing astronauts to extended risks. **B·** Busy ports receive thousands of cargo containers per day, and monitoring their contents for nuclear threats is critical to national security. SSND could be mounted on quadrotor drones for aerial surveillance of port facilities.





**C·** Neutrons are very small and pass easily through most substances that block other forms of radiation. They are therefore extremely difficult to detect, due to lower interaction probability with sensor materials. **D·** A prototype handheld SSND unit. Commercial units will be much smaller. **E·** A highly compact, ultra-high-purity silicon neutron detector element is seen to lower left, the detector seated in boron-coated polyethylene at center, and a complete detector unit to upper right.

# BETTER VISION IN THE DARK

## THE UNSEEN INFRARED PORTION OF THE ELECTROMAGNETIC SPECTRUM OFFERS AN AMAZING VARIETY OF INFORMATION ABOUT PHENOMENA IN THE UNIVERSE.

IN THE LAST DECADE, JPL has pioneered the development of a new family of infrared focal planes based on unique energy bandgap engineering of III-V semiconductor materials. Specialized crystals are “grown” one atomic layer at a time into engineered artificial structures called superlattices to create devices that detect these low-energy infrared (IR) photons. The superlattices can be grown as large uniform arrays that enable wide-field imaging at high resolution. JPL has made numerous advances in infrared detection technology, including high operating temperature barrier infrared detectors (HOT-BIRDs).

NASA low-cost and small satellite mission requirements are driving the development of infrared sensor systems to be smaller, lighter, and less power consuming, while continuing to provide high spatial and thermal resolution. Many other IR focal plane technologies operate at temperatures near that of liquid nitrogen and require large, power-hungry cooling systems. These new HOT-BIRD focal planes allow the use of light-weight passive radiative cooling techniques that require no power for many Earth and planetary observational instruments, including CubeSat applications.

Thermal IR instruments are vital to NASA space and Earth science studies, including missions studying global ecosystems that will provide critical information on natural disasters such as volcanoes, wildfires, and drought. They will monitor and measure pollution, relative humidity profiles, the distribution of different gases in the Earth’s atmosphere, and even gases in other planetary atmospheres. These focal planes will enable wide-field imaging and hyperspectral sounding in the long-wave IR and the very long-wave IR, to observe transient thermal phenomena such as volcanoes and forest fires.

The JPL IR focal planes are currently baselined for multiple upcoming NASA space and airborne instruments. In addition, they are ideal for a variety of ground- and space-based applications such as night vision, early warning systems, navigation, flight control systems, weather monitoring, security, and surveillance.

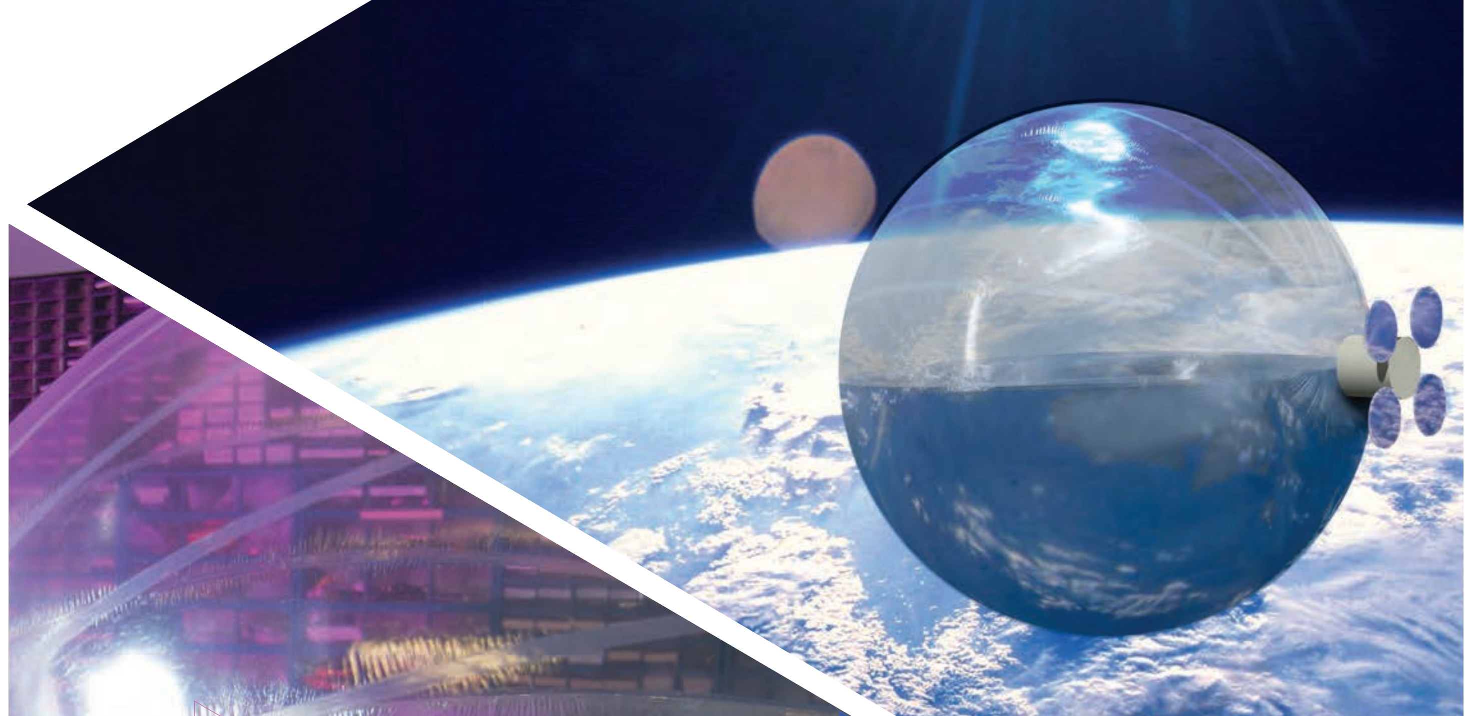
The development of focal plane arrays for infrared imaging is made possible through investment by NASA, the Department of Defense, and other government agencies and private industry.

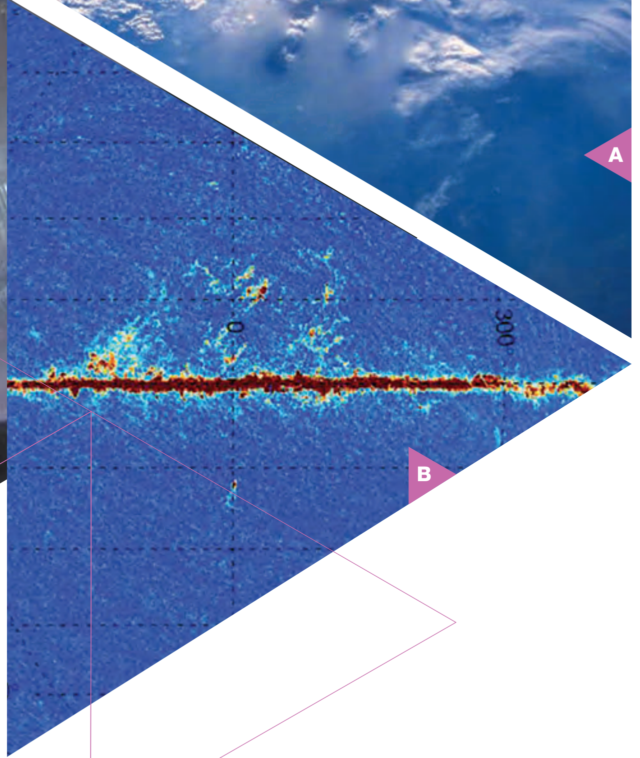
The JPL IR focal planes are currently baselined for multiple upcoming NASA space and airborne instruments.

**A**· Nighttime image of the Griffith Observatory in Los Angeles taken with a barrier infrared detector. **B**· Thermal IR image of an Andean volcano indicating new volcanic activity. **C**· A high operating temperature (HOT) mid-infrared VGA format BIRD focal plane array wafer contains many detector arrays.

Dr. Arezou Khoshakhlagh, using a Veeco Gen 3 **molecular beam epitaxy reactor, “grows” artificial** crystal structures called superlattices.

Dr. Maria Alonso monitors the inflation of a 3 foot (1 meter) prototype inflatable antenna. The top half is transparent to RF, while the bottom is coated with reflective material.





# INFLATABLE ASTRONOMY

DEPLOYING ANTENNAS IN SPACE CAN BE TRICKY BUSINESS, INVOLVING COMPLEX AND MALFUNCTION-PRONE MECHANICAL SYSTEMS. INNOVATIVE RESEARCH AT JPL HAS RESULTED IN INFLATABLE ANTENNAS THAT CAN EXPAND TO MANY TIMES THE DIAMETER OF THE WIDEST ROCKET FAIRING, PROVIDING MORE CAPABLE RADIO TELESCOPES IN ORBIT AND BEYOND.

**IT IS A SIMPLE IDEA:** coat one-half of an inflatable plastic ball with a reflective surface, allowing it to act as an antenna, receiving signals through the other, untreated half of the sphere. JPL's Plastic Inflatable Spherical Antenna (PISA) is designed to provide the large-area antennas needed for radio astronomy.

PISA is designed to solve problems in radio astronomy using this technology. To date PISA has been tested at about 3 feet (1 m) in diameter, and it's so compact before inflation that even a CubeSat could carry an inflatable antenna several times its own width. The design is also scalable, suggesting that much larger antennas can be successful.

Deployment is simple—once the compressed plastic sphere is released, it is inflated until taut. PISAs can be rigidized using coatings that harden when exposed to ultraviolet light. Ideally, the inflated structure would be a parabola, but such shapes have proved difficult to deploy reliably. Theoretical modeling and experiments have confirmed that small discrepancies in surface shape can be corrected by special feeds and optics.

Astronomical observations at radio to submillimeter wavelengths from Earth orbit and beyond are important drivers for this new technology. PISA's larger antenna potential would increase the sensitivity and angular resolution of orbiting radio telescopes. Future missions might include mapping the abundance of water in space, which is of interest not only due to its biogenic importance, but also because it is a major coolant of gas clouds in interstellar regions collapsing to form new stars. In addition, astrophysicists want to follow the "water trail"—from its origins within interstellar clouds to protostellar disks, to solar system objects such as comets, and even to the Earth and other worlds.

But so much water is present in our own atmosphere rendering ground-based observations of weak water signatures from space impossible—these measurements must be conducted from beyond our atmosphere.

Also of interest would be a CubeSat utilizing PISA technology to make an all-sky survey of the interstellar medium in the Milky Way. Key spectral lines are the submillimeter transitions of the carbon monoxide molecule (CO), and the fine structure transition of ionized carbon (C+).

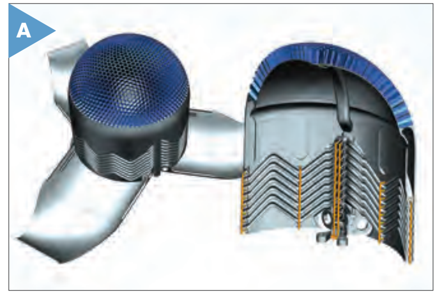
The Planck mission imaged CO over the whole sky, but had no way to determine the velocity of the interstellar clouds observed. A satellite that included a roughly 3-foot (1-m) PISA antenna, equipped with a low-noise Monolithic Microwave Integrated Circuit amplifier and digital spectrometer (all under development at JPL), could measure the motions of thousands of interstellar clouds in and around the Milky Way. This would lead to a better understanding of our galaxy and its surroundings.

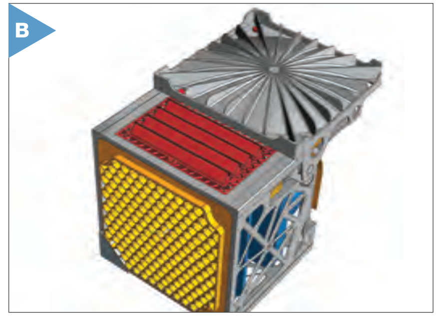
> It is a simple idea: coat one-half of an inflatable plastic ball with a reflective surface, allowing it to act as an antenna.

**A-** Artist's concept of a 28-m-diameter spherical reflector for a terahertz space telescope.
**B-** Planck Space Telescope carbon monoxide map of our galaxy. A spherical antenna radio astronomy observatory could perform spectral measurements and determine the velocity of CO around the central galactic bulge.

# STRUCTURAL CHAMELEON

MUCH OF A SPACECRAFT'S STRUCTURE IS DESIGNED TO WITHSTAND THE INTENSE STRESSES OF LAUNCH. ONCE IT HAS REACHED A REDUCED GRAVITY ENVIRONMENT, THE STRUCTURAL MASS INTENDED TO PROTECT IT FROM LAUNCH LOADS IS NO LONGER REQUIRED. WHAT IF WE COULD REPURPOSE THE STRUCTURE OF OUR SPACE SYSTEMS, INFUSING ACTIVE AND PASSIVE FUNCTIONS, SUCH AS EMBEDDED THERMAL CONTROL OR POWER LINES, INTO THE GEOMETRY OF THE SUPPORTING STRUCTURE?





**A**- 3-D CAD model of a multi-functional 4-D printed sensor case for cryogenic cooling. This is the second generation of 4-D design. **B**- Graphic shows a CAD model of the first 4-D printed architectures. Under a 1U CubeSat form factor, several functions were printed such us optimized structures, passive thermal management systems, integrated power lines, and spring actuated deployables—all contributing to the structural integrity of the system. **C**- Printed spherical honeycomb structure optimized to behave as a cryogenic thermal radiator for passive thermal control. **D**- Printed integrated power lines detail. **E**- Shock-absorbent structure for hard landing systems using lattices. **F**- 3-D printed prototypes of 4-D architecture systems in multiple materials (e.g., aluminum, titanium, polymers) incorporating a wide variety of integrated spacecraft components.

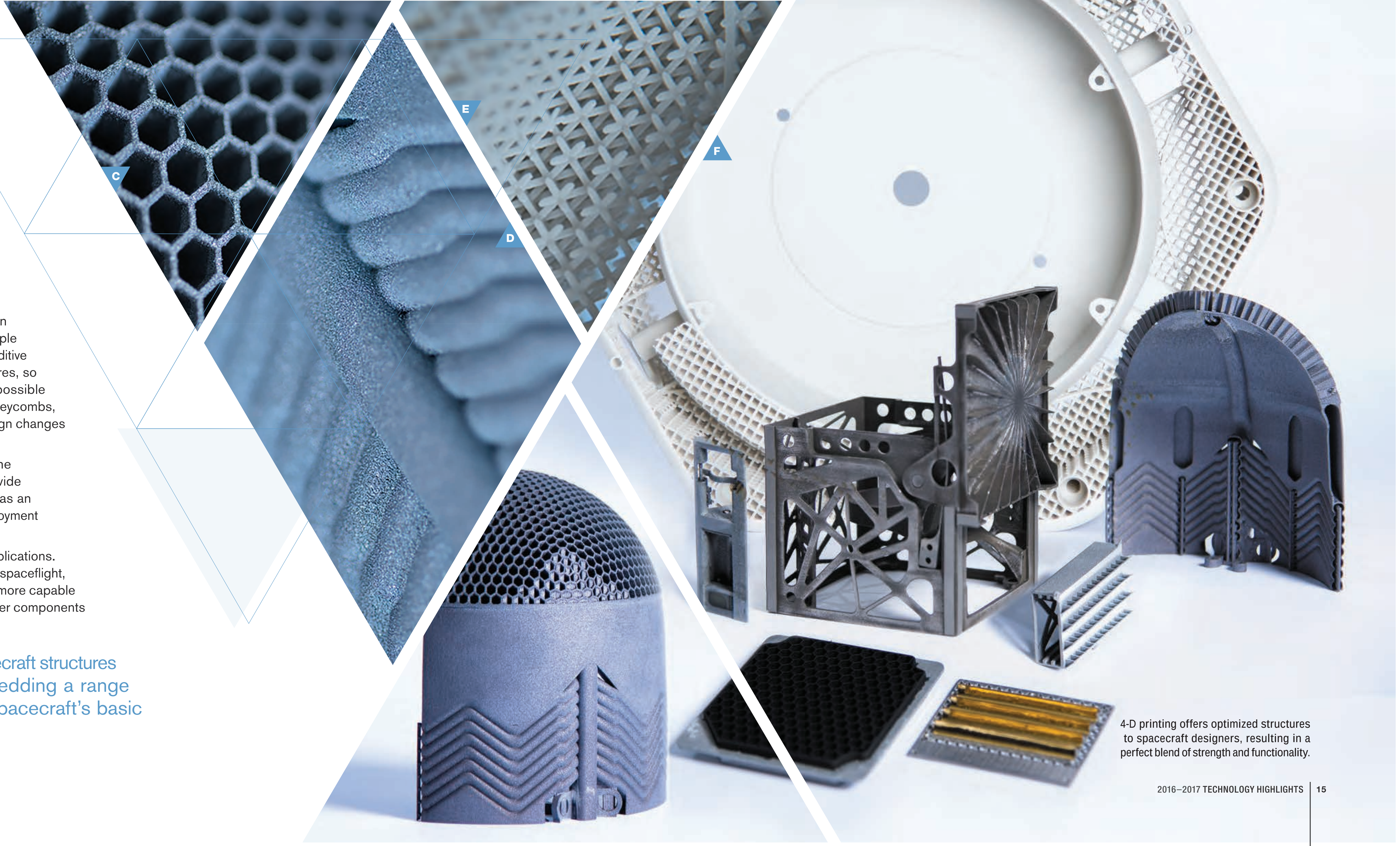
**THE RESULT WOULD BE MORE SCIENCE RETURN.** These multifunctional structures allow additional capabilities to be embedded into the structure without adding mass, creating more opportunity for larger science payloads. Newly developed 3-D printing fabrication techniques enable a range of mechanical and even electronic functions to be embedded into a spacecraft's basic structural components.

The developers call this technology 4-D printing, a new spin on 3-D additive manufacturing. In a process developed by JPL and utilized by its partners in private industry, sintered metal is used to create components that serve multiple purposes over the course of the mission—the 4th "dimension" in the process. Additive manufacturing allows for more complex shapes and highly optimized structures, so that mass is included only where needed. Such designs are impossible with more traditional machining methods—some involve enclosed interior honeycombs, for example—and allow for rapid prototyping and design iterations. These design changes are just a few keystrokes away.

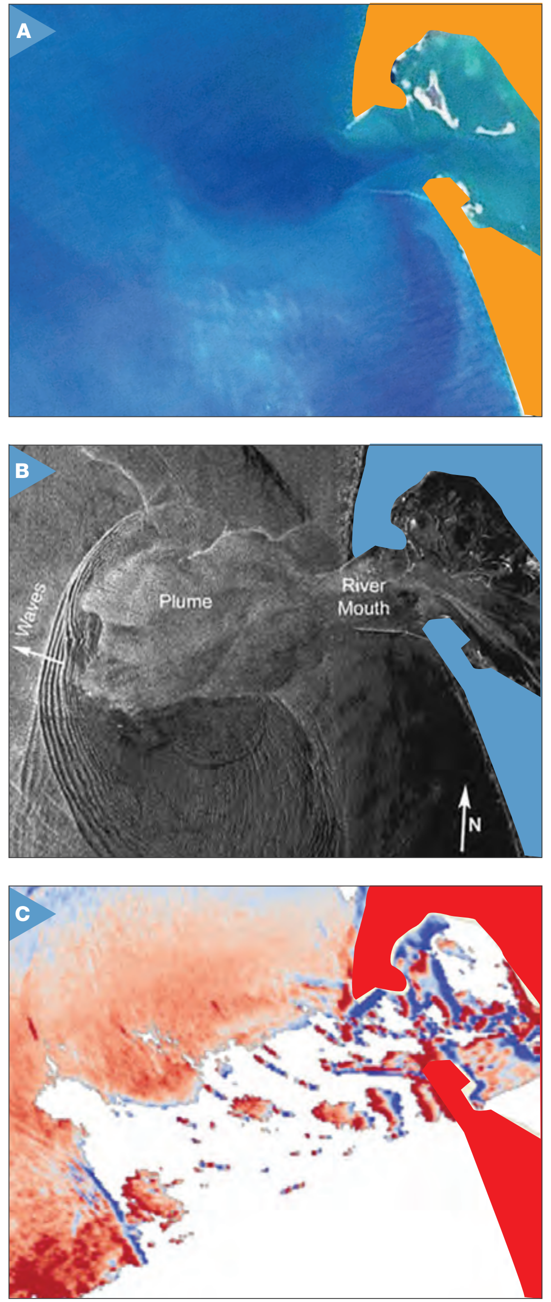
Additive manufacturing allows nonstructural elements to be printed into the framework, optimizing function. The spacecraft bus can be designed to provide power distribution, thermal regulation, radiation shielding, and can even act as an antenna. The printing of hinges and springs into the structure allows for the deployment of spacecraft components without additional parts.

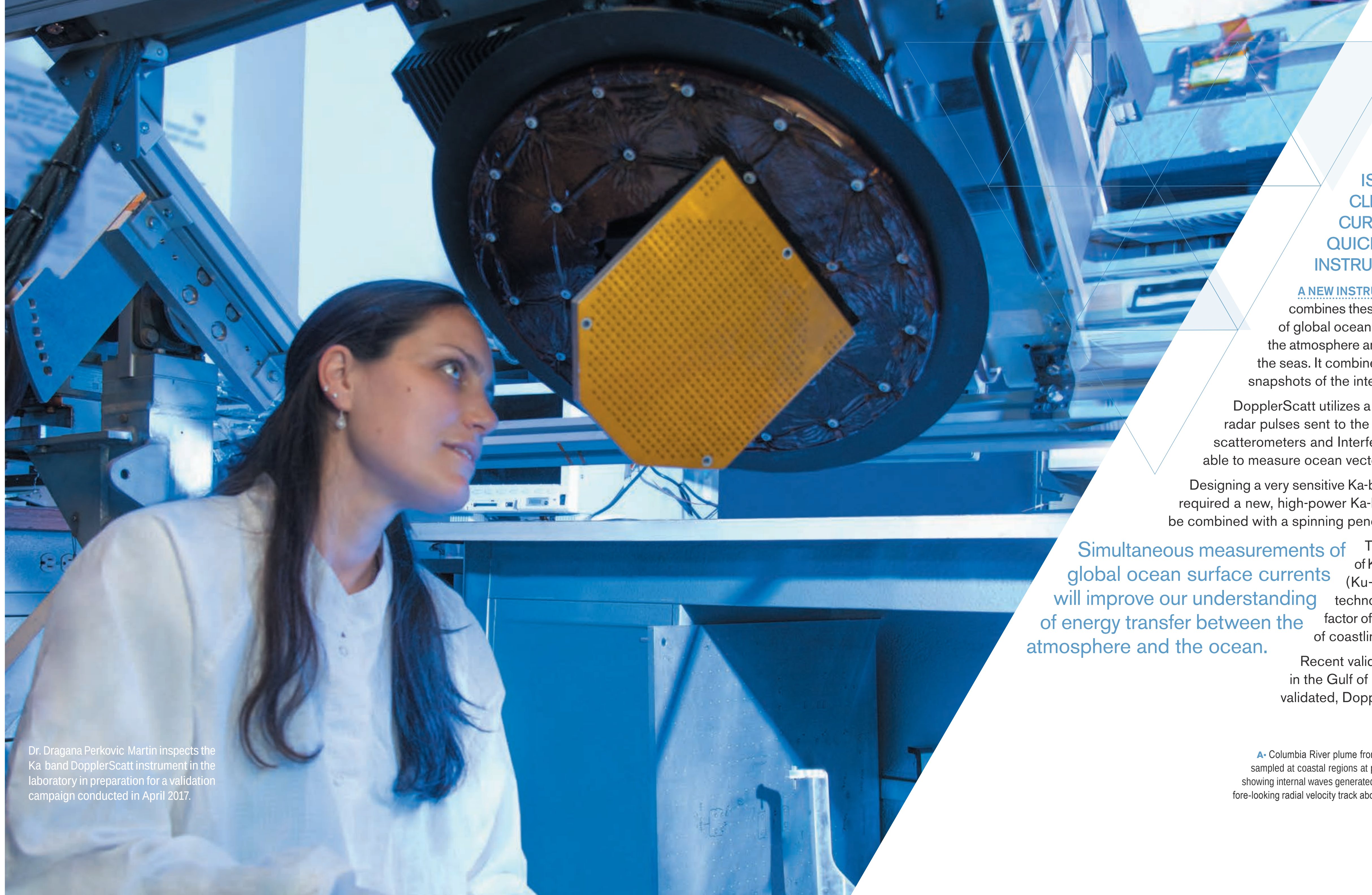
Spinoffs of this technology may find their way into a variety of commercial applications. Examples include automotive design, the construction industry, and defense. In spaceflight, 4-D printed structures will result in rapid development of lighter, stronger and more capable spacecraft. Experiments are underway to print conductors, dielectrics and other components into the structure as it is created, greatly increasing its range of functions.

Newly developed 3-D and 4-D printing fabrication of spacecraft structures promise increased strength with less mass by embedding a range of mechanical and even electronic functions into a spacecraft's basic structural components.



4-D printing offers optimized structures to spacecraft designers, resulting in a perfect blend of strength and functionality.




Dr. Dragana Perkovic Martin inspects the Ka band DopplerScatt instrument in the laboratory in preparation for a validation campaign conducted in April 2017.

# WATCHING WIND & WAVES

OCEAN CURRENTS AND WINDS FORM AN ENDLESS FEEDBACK LOOP: WINDS BLOW OVER THE OCEAN'S SURFACE, CREATING CURRENTS THERE. AT THE SAME TIME, THE HOT OR COLD WATER IN THESE CURRENTS INFLUENCES THE WIND'S SPEED. THIS DELICATE DANCE IS CRUCIAL TO UNDERSTANDING EARTH'S CHANGING CLIMATE. INSTRUMENTS ALREADY EXIST THAT MEASURE OCEAN CURRENTS, AND OTHERS THAT MEASURE WIND, SUCH AS NASA'S QUICKSCAT AND RAPIDSCAT. BUT A NEW AIRBORNE RADAR INSTRUMENT IS ABLE TO MEASURE BOTH SIMULTANEOUSLY.

A NEW INSTRUMENT DEVELOPED AT JPL, the Ka-band Doppler Scatterometer (DopplerScatt), combines these abilities into a single, space-capable instrument. Simultaneous measurements of global ocean surface currents will improve our understanding of energy transfer between the atmosphere and the ocean, as well as the movement of heat, nutrients, and pollutants across the seas. It combines observations of the surface over a wide swath and enables high-resolution snapshots of the interacting ocean and atmosphere unavailable from previous instruments.

DopplerScatt utilizes a spinning antenna to measure backscatter and Doppler signals from pairs of radar pulses sent to the ocean's surface. This unique design combines the properties of traditional scatterometers and Interferometric Synthetic Aperture Radar (InSAR) instruments, each of which is able to measure ocean vector winds or surface currents, but not both.

Designing a very sensitive Ka-band instrument that would have high signal-to-noise and cover a large swath required a new, high-power Ka-band amplifier with a long duty cycle, approximately 50 percent, that could be combined with a spinning pencil-beam antenna.

Simultaneous measurements of global ocean surface currents will improve our understanding of energy transfer between the atmosphere and the ocean.

This was the first successful test of these technologies used in combination. The use of Ka-band instead of the lower frequencies traditionally used for wind measurements (Ku- or C-band) has the advantage of being smaller and lower mass. This technology has also increased the surface current measurement performance by a factor of up to nine compared to Ku-band instruments, and enables closer observations of coastlines, a region of great interest for environmental monitoring.

Recent validation campaigns include flyovers of the Columbia River plume and oil drifts in the Gulf of Mexico on a DOE King Air B200 aircraft. Now that the instrument has been validated, DopplerScatt is available for use on future NASA airborne science missions.

**A**▪ Columbia River plume from space. The campaign goals were to provide the first validation for the winds and currents measurement concept sampled at coastal regions at previously measured and modeled sites. **B**▪ Satellite SAR image of the Columbia River plume from August 9, 2002, showing internal waves generated by the plume. **C**▪ The first DopplerScatt validation campaign took place September 12–17, 2016. Shown is a Track 1 fore-looking radial velocity track above the Columbia River plume.

# TREASURE IN THE DARKNESS

NASA'S DEEP SPACE NETWORK (DSN) IS THE WORLD'S PREMIER SPACECRAFT TRACKING AND CONTROL SYSTEM, SPREAD ACROSS THREE CONTINENTS AND OPERATIONAL SINCE 1958. WHILE THE DSN'S PRIMARY PURPOSE IS SPACECRAFT COMMUNICATION, NEW JPL SOFTWARE TAPS ITS POTENTIAL AS A RESOURCE FOR ASTRONOMICAL SCIENCE.

THE THREE TRACKING complexes communicate with spacecraft 24 hours per day, but only a small percentage of the system's bandwidth is needed for communication. In addition to communication signals sent by spacecraft, there is a constant flow of radio wave signals emanating from deep-space sources. JPL's Space Network Transient Observatory (DTO) detects and utilizes these additional signals to conduct planetary and deep-space astronomy.

Why hasn't this been done before? The key is new and innovative computer hardware and software that can sift through the huge amounts of data that a radio dish receives while communicating with spacecraft. During communication sessions, the dish is also receiving data from the background. Filtering relevant science from the overall signal is called spectrum analysis, and was first developed for military applications, but the hardware required to enable it is more closely related to an Xbox than spy satellites. The DTO is not an additional facility, but consists of a single hardware rack at the DSN's Goldstone Signal Processing Center, running the specialized algorithms that analyze DSN data for signals of interest to researchers.

Examples of what the DTO is able to investigate include such high-profile topics as fast radio bursts (FRBs) from distant stars and electrical discharges in the Martian atmosphere. While both phenomena can be studied with targeted observations, scheduling time on large radio dishes is expensive and observing slots are limited. With DTO, when targets of interest coordinate with DSN duties, the observation time is virtually free. And since spacecraft on Mars communicate with Earth daily, observations of the Red Planet are virtually guaranteed.

The electrical events on Mars are of particular interest to NASA, as they may affect both robotic and human missions to the planet. These electrical discharges appear to be associated with dust storms, and could potentially endanger spacecraft electronics. They may also change the chemistry of the local atmosphere, possibly making it more corrosive. Astronauts visiting Mars would need to be aware of incoming electrical storm fronts.

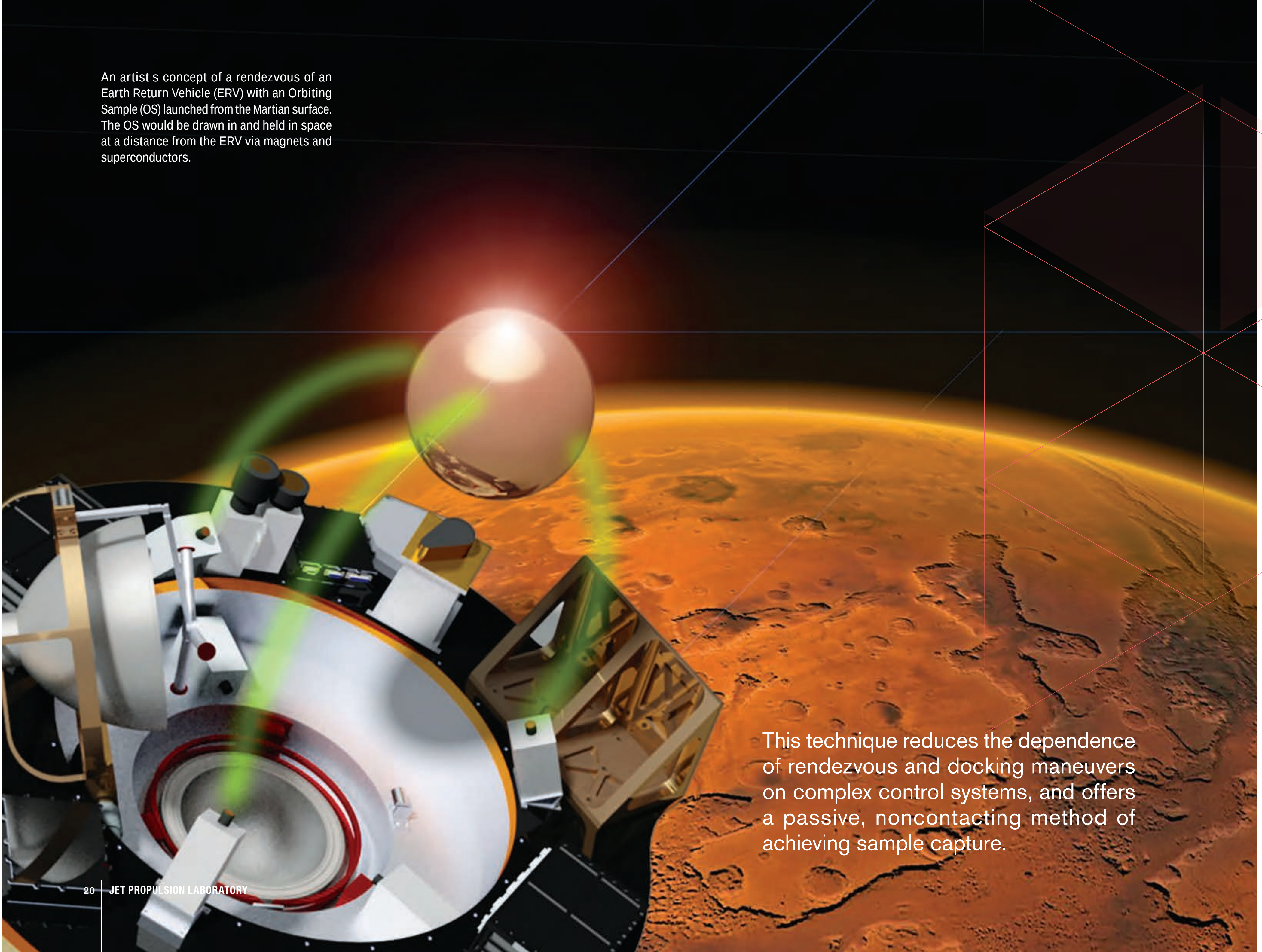
> In addition to communication signals sent by spacecraft, there is a constant flow of radio wave signals emanating from deep-space sources. JPL's DTO detects and utilizes these additional signals to conduct planetary and deep-space astronomy.

Another area of interest is the search for extraterrestrial intelligence, or SETI. Since DSN dishes spend long periods of time tracking a fixed area of sky, it makes sense to parse collected data for artificially generated signals. This would expand the limited amount of SETI investigation currently taking place.

The hardware for DTO is already installed and tested, and current goals include configuring it to run in the background unattended. The program makes no special demands on the DSN; it merely sorts through the incoming signal, and alerts astronomers if anything interesting is detected. Simple changes to the firmware in the DTO's electronics can target specific areas of interest, and are accomplished by a few commands sent from a researcher's computer. DTO is humanity's newest outward-looking sentinel, continually searching the skies for items of scientific interest.

A- Shown here is the Deep Space Network's Goldstone 1 communication station. The DTO utilizes additional signals emanating from deep space to conduct planetary and deep-space astronomy. B- Electrical activity has been measured in Martian dust storms—a phenomenon of particular interest to mission planners.

While a Deep Space Network antenna is communicating with a spacecraft near Mars or any other target, it is also collecting a large amount of data from the surrounding sky, or in this case, a lightning discharge on the surface of Mars.



An artist s concept of a rendezvous of an Earth Return Vehicle (ERV) with an Orbiting Sample (OS) launched from the Martian surface. The OS would be drawn in and held in space at a distance from the ERV via magnets and superconductors.

This technique reduces the dependence of rendezvous and docking maneuvers on complex control systems, and offers a passive, noncontacting method of achieving sample capture.

# THE SCIENCE OF MUTUAL ATTRACTION

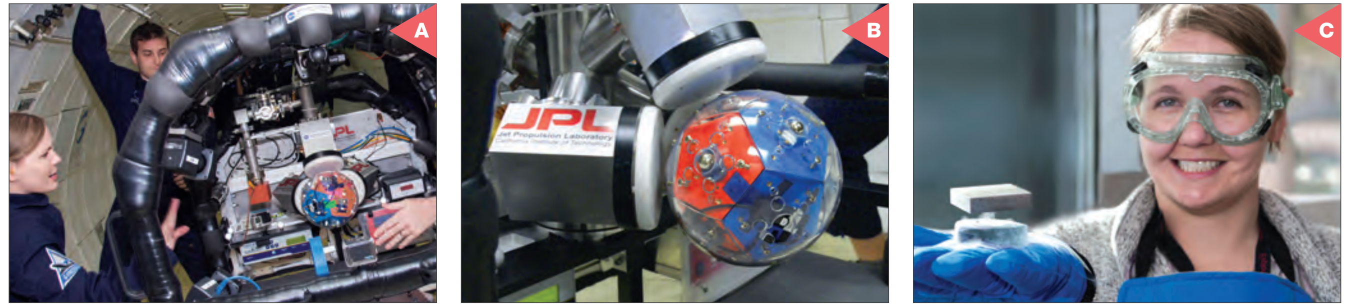
SAMPLE RETURN MISSIONS HAVE BEEN COVETED BY PLANETARY SCIENTISTS FOR DECADES, BUT RENDEZVOUS, DOCKING, AND SAMPLE CAPTURE ARE CHALLENGING SPACECRAFT OPERATIONS THAT REQUIRE COMPLEX MECHANICAL SYSTEMS AND SOFTWARE. JPL RESEARCHERS ARE DEMONSTRATING A NEW TECHNIQUE THAT MAY OPEN UP INNOVATIVE WAYS TO COMPLETE THIS PROCESS USING MAGNETS AND SUPERCONDUCTORS.

WHILE REMOTE AND IN SITU ANALYSES of the Martian surface have yielded vast scientific discoveries, nothing compares to bringing a sample back to Earth. First-hand scrutiny of a few grams of Martian soil (or samples from elsewhere in the solar system) is a long-held dream of planetary scientists, but the complex choreography involved in returning a sample from another planet, its moons, a comet, or an asteroid is daunting. Thanks to new research spearheaded by JPL, this task may become easier.

Traditional sample return designs use robotic arms or cones to dock with orbiting samples, systems that can require complex active control especially to close the last few centimeters and make contact with an uncontrolled object. This new technique uses superconducting physics and magnets to bring two spacecraft together passively. Unlike magnets alone, the physics of magnetic flux pinning can bring the two spacecraft to a stable proximity relative to each other without active position control or contact between the spacecraft. This technology was first developed at Cornell University, and JPL is investigating ways to leverage it to capture orbiting samples.

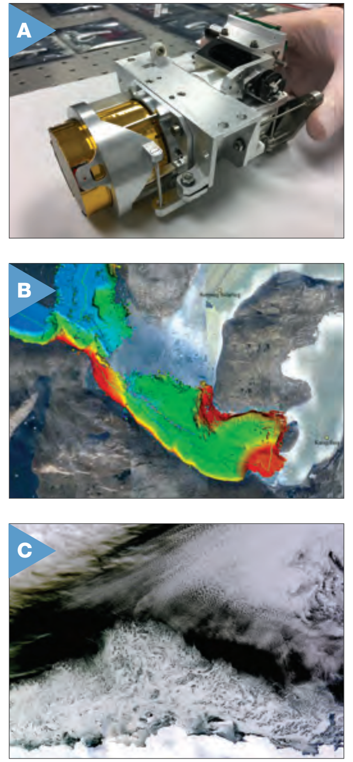
A Mars sample return mission using magnetic flux pinning might look like this: sometime in the 2020s, a Mars Ascent Vehicle has brought Martian samples into Martian orbit. This Orbiting Sample (OS) vehicle has permanent magnets embedded in its structure. The Sample Return Vehicle (SRV), which has subsequently been sent into Martian orbit, contains a set of superconductors and a set of permanent magnets with a flux distribution that matches the OS. When it is time for the two to rendezvous, the superconductors on the SRV are chilled to induce a superconducting state, then permanent magnets matching those embedded in the OS are used to “train” the superconductor. These training magnets are then removed, clearing the capture area for docking. As the OS vehicle nears the SRV, the superconductor “remembers” the magnetic flux signature and draws in the permanent magnets on the OS from up to about 18 inches (0.5 m) away, and the two are able to rendezvous safely, with the OS being magnetically held at a slight standoff. Even if the OS is tumbling, the superconductors would act to drive it into the proper configuration without any mechanical contact or position control systems. Safely captured by the SRV, the unopened sample cache can then be cleaned or bagged before returning to Earth.

This technique reduces the dependence of rendezvous and docking maneuvers on complex control systems, and offers a passive, noncontacting method of achieving sample capture. This technology may also help to alleviate planetary protection concerns by breaking the potential chain of contamination. A successful demonstration in a microgravity aircraft flight—which allows for six degrees of freedom—occurred in March 2017.



**A-** A JPL team successfully tests magnetic flux pinning aboard a microgravity simulation flight. **B-** The Orbiting Sample is positioned to be magnetically captured by the superconductors aboard the Earth Return Vehicle. **C-** Principal Investigator Laura Jones-Wilson demonstrates magnetic flux pinning.

# TWO FOR ONE: WATER & SNOW



A- SWIS is small enough to be flown as a ride-along on the open decks of commercial communication satellites, resulting in greatly reduced cost of operation. B- The ability to observe icy or snow-covered coastal environments is critical to monitoring interactions between freshwater runoff and saline coastal ocean waters. C- The Antarctic coast is a critical region to monitor the ice/ocean boundary, as increasing melting has a direct impact on salinity and sea life.

IN SPACEFLIGHT, GETTING TWO SETS OF IMPORTANT SCIENTIFIC DATA FOR THE PRICE OF ONE IS ALWAYS A BENEFIT. THE SNOW AND WATER IMAGING SPECTROMETER (SWIS) COMBINES THE ABILITY TO IMAGE SPECTRA FROM THE DARK SURFACE OF THE COASTAL OCEANS AND BRIGHT SNOW NEARBY SIMULTANEOUSLY.

**PREVIOUS TECHNOLOGIES** have succeeded in imaging both oceans and snowy peaks, but always with separate instruments, many of which must be flown in airplanes. JPL researchers recognized the value of a spacecraft that could continuously monitor both types of terrain using just one instrument in Earth orbit. Observing the interaction between freshwater runoff from snow and glaciers, and how it mixes with the saline shoreline waters, is critical to understanding the effects of changing temperatures on plankton and other sea life in these environments.

Designed to fly in a compact CubeSat configuration, SWIS utilizes a high dynamic range to accomplish imaging spectra from both snow and water, which run the gamut from blindingly white to a dark blue. The trick to achieving this is a detector with a fast readout, combined with a spectrometer that possesses high sensitivity.

JPL has decades of experience in designing extremely sensitive, high-precision spectrometers, but placing such a broadly capable instrument in a small package is a very challenging task. In the past, a single spectrometer capable of observing just one of these regions was typically about the size of a dishwasher. Using sophisticated optical design, SWIS compresses the technology required for both tasks to a 6U CubeSat about the size of a traffic pylon, with correspondingly lower power requirements.

But data are only as useful if the quality is high. SWIS contains an onboard calibration capability to assure that the data received is of consistently high quality over the life of the spacecraft. A small constellation of such satellites would allow for continuous observation of Earth's coastlines, critical to understanding the dynamic changes that take place there. Examples include the coasts of Greenland and the Antarctic, where freshwater flow from glaciers and icy cliffs impinge on the saline ocean environment of the shoreline, dramatically altering the ecology of the region.

Traditional spectrometers can gather vast amounts of data but have little dwell time when carried over the region in aircraft. SWIS can take its time, creating denser measurements of a given area and generating more in-depth observations. SWIS has the added advantage of using many off-the-shelf parts, resulting in lower cost.

In this era of melting glaciers, diminished snowpacks, and encroaching drought, technology such as SWIS is critical to enhanced, round-the-clock monitoring of these resources and coastal marine ecosystems from a stable platform in space.

> Designed to fly in a compact CubeSat configuration, SWIS utilizes high dynamic range detection to accomplish imaging spectra from both snow and water, which run the gamut from blindingly white to a dark blue.

The Snow and Water Imaging Spectrometer represents the first space spectrometer compatible with CubeSat dimensions that can simultaneously observe bright snow and dark water.

Dr. Marshall Smart inspects a custom electrolyte in an environmentally controlled glove box. JPL has developed advanced Li-ion electrolyte formulations needed for deep-space missions.

# POWER RANGER

ANYONE WHO HAS HAD THEIR LAPTOP DIE IN THE MIDDLE OF A CRITICAL TASK KNOWS THAT BATTERIES DON'T LAST LONG ENOUGH. SPACECRAFT DESIGNERS HAVE THE SAME PROBLEM. DESPITE DECADES OF RESEARCH, BATTERY STORAGE ABILITY IS LIMITED, AND IS ADVERSELY AFFECTED BY EXPOSURE TO COLD AND EXTENDED USE CYCLES. JPL'S NEW LITHIUM-ION BATTERY ELECTROLYTES ARE ADDRESSING THESE CONCERNS AND INCREASING BATTERY LIFE AND OPERATIONAL TEMPERATURE RANGE.

**DEEP-SPACE MISSIONS TYPICALLY** use either Radioisotope Thermoelectric Generators (RTGs) or solar panels to charge lithium-ion (Li-ion) batteries that in turn provide steady, consistent power to the spacecraft. But batteries have a limited run time, and for extended missions must be recharged regularly. Once recharged, the clock is ticking and the longer they can deliver power, the better. For example, operations may need to be sustained during times when solar power is unavailable. While RTGs can sustain continuous power, they are comparatively expensive and the plutonium that powers them is a limited resource. Finally, for some short missions the batteries are not recharged, and once the batteries run down the mission is over. Hence, a focus of the research has been on extending the life and efficiency of Li-ion batteries.

JPL has been developing new electrolytes—the chemicals that allow a conductive pathway between the two electrodes enabling efficient charge and discharge—that offer increased efficiency. While commercial battery suppliers work continuously to improve battery technology, their goals are usually quite different than those required for spaceflight. Commercially available batteries may store power well, but not be spaceflight friendly due to their mass, or may be incapable of withstanding the rigors of spaceflight. It's also essential that any batteries used in space be able to operate effectively across a broad temperature range.

JPL's high-tech electrolytes use low-viscosity co-solvents to improve function in extreme cold without the need for onboard heaters, which are not always available on smaller probes and rovers. For future missions, such as to icy moons, engineers hope to improve not just the discharge power capability, but also to optimize the recharging characteristics for batteries that are operating at about minus 40 degrees F (−40C), since this is the expected internal environment of thermally managed probes to such destinations. Eliminating dedicated battery heaters will also result in lowered spacecraft mass. These new chemical formulations will also offer improved battery cycle life as well as better low-temperature performance here on Earth, a potential lifesaver for people living and working in severe winter conditions.

JPL's pioneering research in Li-ion battery electrolytes has enhanced battery cycle life and improved performance at low temperature.

**A·** The Li-ion batteries on the Juno spacecraft contain a JPL-developed high-efficiency electrolyte, and store electrical power for use when the solar panels are not exposed to sunlight. **B·** JPL-developed Li-ion electrolytes have been successfully used on a number of missions, including MER and MSL, and will power InSight. **C·** The performance of prototype Li-ion cells containing advanced electrolytes is tested under mission-relevant electrical and thermal profiles.

# SURVIVING IN SPACE

PLANETARY EXPLORATION INVOLVES SPACECRAFT WORKING IN HARSH AND UNFORGIVING ENVIRONMENTS, SUCH AS THE HOSTILE RADIATION BELTS SURROUNDING JUPITER, THE FROZEN WASTES OF THE MARTIAN POLES, OR THE CORROSIVE ATMOSPHERE OF VENUS. JPL IS PIONEERING RESILIENT, SELF-AWARE AND AUTONOMOUS SYSTEMS, ABLE TO WEIGH RISK AND MAKE DECISIONS ON THE SPOT, WHICH WILL BE INCREASINGLY VITAL TO MISSION SUCCESS.

IN RECENT YEARS, projects such as the Curiosity rover on Mars and the Cassini probe at Saturn have benefited from enhanced autonomy—many functions can be performed without waiting for commands from the ground that can take from 30 minutes to many hours to make a round trip. New research at JPL is driving spacecraft autonomy forward, offering future missions an increased awareness of their current functionality status and surroundings, knowledge of their operational options and the associated risks, and an ability to weigh these risks against possible rewards.

Newly complex and ambitious investigations of distant worlds increasingly take humans out of the loop, and demand greater levels of artificial intelligence and onboard control to carry out complicated tasks. These will include orbital injections at distant worlds, rovers crossing unmapped surface terrain, complicated sample return missions, and planetary entry, descent, and landing. Autonomous decision-making depends not just on a knowledge of what happened before, but predicting and weighing what might happen next, with the fullest possible awareness of the spacecraft's condition and the environment in which it is operating. In effect, the machine needs to understand risk, and make related decisions on the spot. We have seen this need for risk-aware autonomy demonstrated during missions such as the Mars Exploration Rovers, when Spirit got trapped in a sand drift, eventually ending its journey.

The major accomplishments of this project to date include development of planning and execution algorithms that are innovative in their use of risk as a driving consideration, and the integration of these algorithms into the Resilient Spacecraft Executive (RSE), a modular canonical software architecture that lends itself to further extension and reconfiguration. Multiple deployments of the integrated RSE capabilities on various different platforms and simulation environments have been successfully carried out, and highlight the broad applicability and versatility of this approach. A test using Mars rover scenarios has demonstrated resilience to off-nominal situations, such as replanning safer routes to the next science site in the presence of terrain hazards, and recovering from a sampling drill bit failure. A demonstration using an autonomous underwater vehicle involved replanning the mission to mitigate risks associated with spatial and temporal changes in ocean currents.

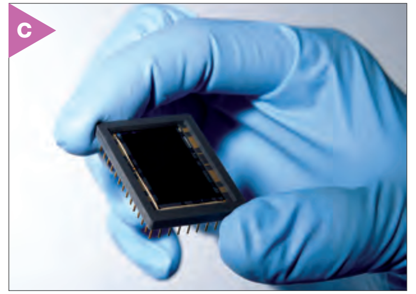
In the future, spacecraft will have the ability to "fly through failure" by immediately choosing the best course of action within the given circumstances. Such "graceful degradation" allows for continued progress towards mission goals despite component failures. This autonomous architecture will soon play a central role in assuring a scientifically rich return on our investment in the exploration of the solar system.

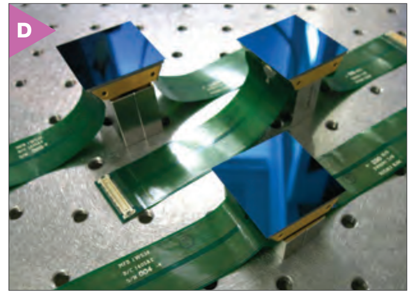
The Resilient Spacecraft Executive was developed in partnership with Caltech, MIT, and the Woods Hole Oceanographic Institution, with funding from the Keck Institute for Space Studies.

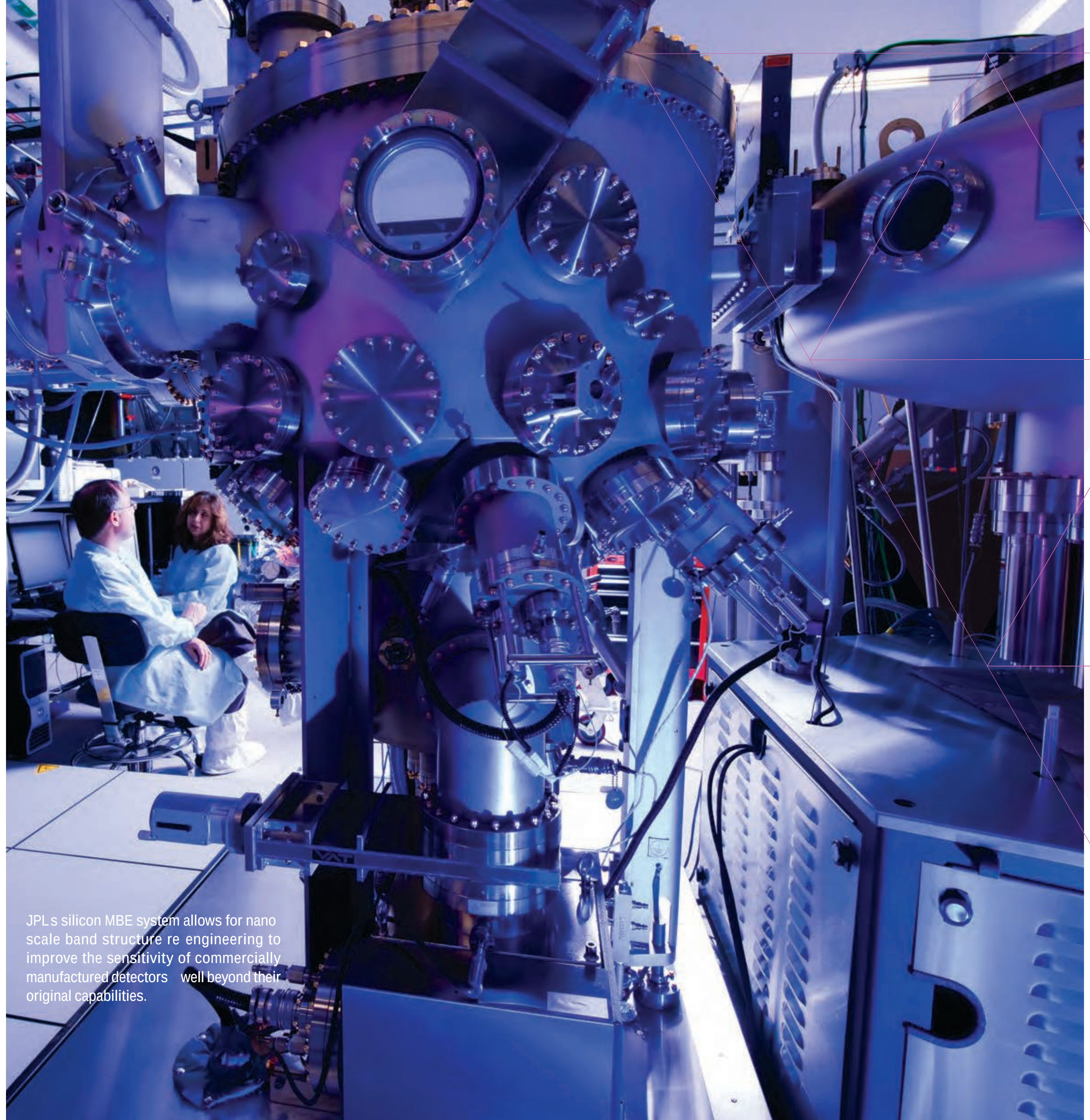
These new resilient systems will increase the spacecraft's level of tolerance for, and the capacity to recover from, failed components and computing errors.

**A·** Risk-aware autonomous software is also useful for underwater vehicles, from terrestrial ocean-going drones to possible future submersibles diving the depths of Titan's oceans, as envisioned here. **B·** Autonomous operations depend on an awareness of not only the immediate environment, but also the condition of the spacecraft. If a component fails, the software undertakes steps to assure "graceful degradation."

**A mission concept for a low-flying orbiter** makes a pass through the watery plumes of Europa. In fast-changing environments such as this, and far from Earth, expanded spacecraft autonomy will be critical to success. *IMAGE CREDIT: Marco Nero.*







JPL's silicon MBE system allows for nano-scale band structure re-engineering to improve the sensitivity of commercially manufactured detectors—well beyond their original capabilities.

# RE-ENGINEERING SILICON

INDUSTRY HAS DEVELOPED DIGITAL CAMERAS FOR OUR SMARTPHONES, OUR COMPUTERS, EVEN OUR CARS, AND THE MASS-PRODUCED SILICON IMAGERS THAT DRIVE THESE DEVICES ARE CHEAP AND RELIABLE. HOWEVER, THESE COMMERCIAL DETECTORS DO NOT MEET THE DEMANDING NEEDS OF ASTRONOMICAL OBSERVATIONS. A NOVEL APPROACH TO RE-ENGINEERING THESE DETECTORS HAS REVOLUTIONIZED ASTRONOMY BY GREATLY INCREASING THEIR SPECTRAL RANGE AND SENSITIVITY.

TODAY, EVERY NASA MISSION includes silicon-based digital imagers in one form or another. The search for ever fainter and more distant objects requires bigger detector arrays that are more sensitive than their predecessors. Researchers at JPL are constantly working to improve detector capabilities to meet NASA's increasing demands, and in some cases this requires re-engineering existing devices at the atomic level.

NASA's spacecraft are probing the mysteries of exoplanets, distant stars, and entire galaxies, and to accomplish this, observations across a variety of spectral wavelength bands are often required. Early silicon detectors were not used for ultraviolet (UV) imaging due to their poor UV sensitivity. In a novel approach, JPL improved detector sensitivity and extended the spectral range to the UV and beyond by inverting the detector and re-engineering the light-collecting surface. This re-engineering is accomplished at the nanoscale level through a process called molecular-beam epitaxy (MBE). MBE is used to grow single layers of crystalline silicon and within that layer is embedded a highly-concentrated, atomically-thin sheet of "dopants"—intentionally positioned impurities that are introduced for the purpose of modifying the detector's electronic properties. This unique process enhances the detector's sensitivity across a broad spectral range spanning X-rays, UV, visible light, and near-infrared wavelengths. Detector sensitivity can then be further "tuned" with custom antireflection coatings and optical filters.

JPL's re-engineering techniques have led to several breakthroughs in silicon-based imaging. A recent example is the development of "solar-blind" silicon detectors. Scientists searching for interesting signals in the UV often find that the weak UV signals are competing with bright visible backgrounds, and the few UV photons are lost amongst thousands of visible photons. JPL's solar-blind detectors include special filters that optimize UV sensitivity while blocking the visible signal, eliminating one of the last obstacles for using silicon detectors in UV-only applications. The processing techniques described above can be applied to any silicon detector, including those with a single-photon counting capability needed for observing ultra-weak sources. Today, JPL's partnership with industry and astronomers has produced record UV sensitivity in photon-counting silicon detectors.

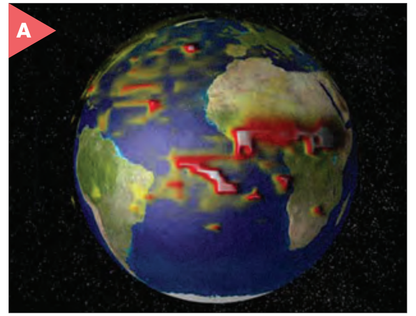
The unique capabilities of JPL's re-engineered detectors have been proven at the Palomar and Mount Bigelow Observatories as well as in suborbital flights. Their future use in spacecraft will open new vistas in astrophysics, heliophysics, and planetary science.

JPL's nano-engineering techniques have led to several breakthroughs in silicon-based imaging vital to future astronomy missions.

**A·** A researcher prepares a device wafer for the band structure re-engineering process. Up to eight 8-inch wafers can be loaded into the MBE at once. **B·** A researcher uses ALD to deposit a customized anti-reflection coating onto a device wafer in order to "fine-tune" its spectral sensitivity. **C·** A photon-counting UV CCD optimized for narrowband operation (200–220 nm). **D·** A trio of imagers with broadband response spanning UV to near-infrared wavelengths (320–1000 nm).

# HUNTING GREENHOUSE GASES

TRACKING THE AMOUNTS AND DISTRIBUTIONS OF GREENHOUSE GASES IN EARTH'S ATMOSPHERE IS CRITICAL TO WEATHER PREDICTION, CLIMATE CHANGE TRACKING, AND HUMAN HEALTH, BUT CAN BE TIME CONSUMING AND EXPENSIVE TO ACCOMPLISH USING CURRENT METHODS SUCH AS PILOTED AIRCRAFT OVERFLIGHT. NEW TECHNOLOGY BEING TESTED BY JPL WILL PROVIDE MORE EFFICIENT "WEATHER REPORTS" FOR GREENHOUSE GASES AND POLLUTANTS FROM SPACE.



**A** • Data from NASA's Tropospheric Emission Spectrometer on the Aura satellite show the relative concentration of ozone in early 2006. Tracking such potentially hazardous gases is a key goal of IFTS. **B** • Ozone vertical profiles are crucial for understanding ozone processes that impact climate and air quality. **C** • From a site near the Mount Wilson Observatory, Los Angeles, a test spectrometer has collected greenhouse gas data of the LA basin for a number of years. Methane to carbon dioxide ratio is shown; magenta identifies the area where the ratio is highest.

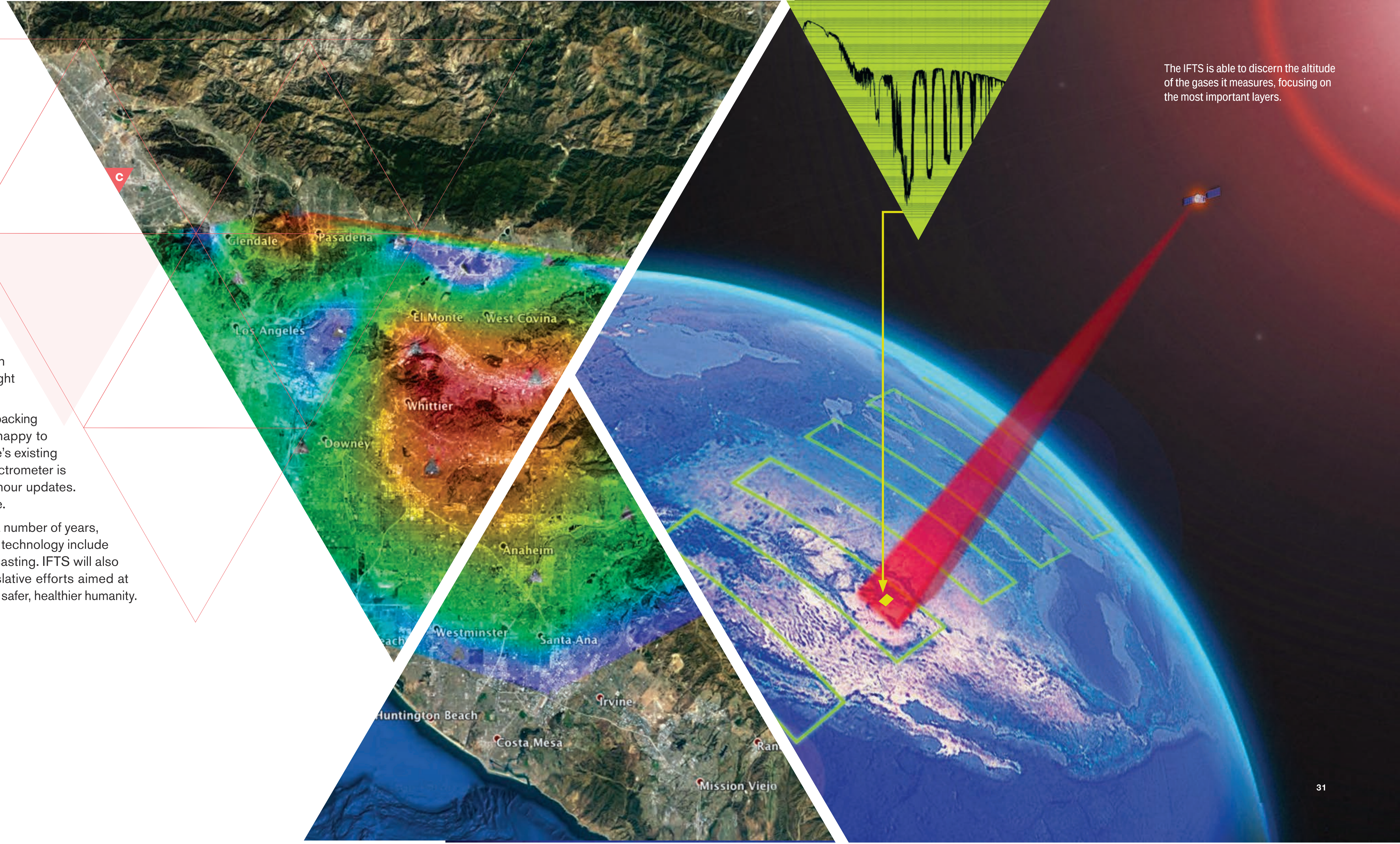
**EARTH'S ATMOSPHERE** is a constantly changing mixture of gases, some natural and some humanmade. The amounts and distributions of these gases are in continual flux, and diligent monitoring is critical to understanding and forecasting climate change. Among the most critical gases to track are ozone and carbon dioxide, as both are involved with Earth's carbon cycle and climate change. Continuous observation of a global nature is needed.

JPL's compact Imaging Fourier Transform Spectrometer (IFTS) may be the solution. This revolutionary new instrument design incorporating a Michelson interferometer at its heart enables simultaneous observations of reflected sunlight and thermal emissions to profile pollutants and greenhouse gases.

Given the small size, low mass, and low power requirements, IFTS is ideal for piggybacking aboard commercial satellites, occupying excess space that the owners are happy to lease. This will reduce mission cost, while allowing the IFTS to utilize the satellite's existing communication and power systems. Perched in geosynchronous orbit, this spectrometer is capable of observing about one-third of Earth continuously, providing hour-by-hour updates. Three IFTS satellites would offer continuous global coverage below 60° latitude.

Components of IFTS have been undergoing tests in the Los Angeles basin for a number of years, and have proven to be extremely reliable and accurate. Additional benefits of this technology include better prediction of air quality in metropolitan areas and improved weather forecasting. IFTS will also provide continuous monitoring of carbon emissions, critical to emerging legislative efforts aimed at curbing greenhouse gases. The net result will be improved climate modeling and a safer, healthier humanity.

Perched in geosynchronous orbit, this advanced compact spectrometer would observe about one-third of Earth continuously, providing hour-by-hour updates of greenhouse gas concentrations.



The IFTS is able to discern the altitude of the gases it measures, focusing on the most important layers.

About the size of a smartphone when collapsed for transport, PUFFERs unfold into two-wheeled crawlers able to traverse a surprisingly diverse range of obstacles, and to right themselves if inverted.

Multiple PUFFERs deployed from a future rover with one preparing to enter a small crevice.

# ORIGAMI ROBOTS

HOW CAN PLANETARY EXPLORATION VEHICLES LEVERAGE HIGH-TECH ORIGAMI? –FOLDING ROBOTS! INNOVATIVE NEW TECHNOLOGY BEING PIONEERED AT JPL WILL ENABLE THE EXPLORATION OF CHALLENGING PLANETARY TERRAIN WITH LOW-COST AND VERY COMPACT ROBOTS–SO COMPACT THAT A SMALL FLEET OF THEM IS ABLE TO RIDE ALONG ON A SINGLE ROVER.

CALLED POP-UP FLAT FOLDING EXPLORER ROBOTS, or PUFFERs, these miniature rovers can cross terrain that is too rugged or dangerous for a traditional rover to attempt—examples include steep sedimentary rock slopes or the underside of eroded overhangs. PUFFERs are about the size of a smartphone when collapsed for transport, then once deployed, unfold into two-wheeled crawlers that can negotiate a surprisingly diverse range of surfaces. They also have the ability to right themselves if inverted.

Deployment of PUFFERs is as simple as their design. When the “parent” rover encounters terrain suited to exploration by a PUFFER, one of the little robots would be ejected, freeing the rover to continue with other tasks. Regardless of how the PUFFER lands, it unfolds and rights itself into the proper orientation to begin exploring independently. An added benefit of this design is that the wheels can be refolded if the PUFFER encounters terrain that requires it to reduce its height–it can reconfigure itself to crawl forward while nearly flat.

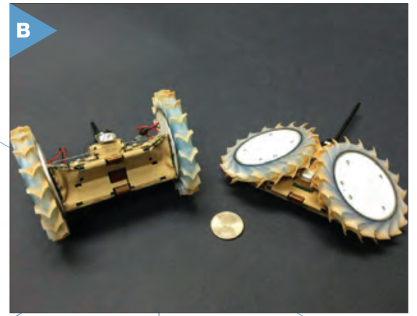
Several of the microbots can be flattened like cards and stacked one on top of the other. The main body of the folding robot is constructed of a printed circuit board that is flexible enough to be folded for transport, a property gained by incorporating innovative materials such as textile circuit boards into their construction. Rapid prototyping was accomplished via 3-D printing. Highly miniaturized instruments are being designed for use aboard PUFFER, including a tiny ground-pointing microscope.

PUFFERs have been extensively tested in terrain ranging from the Mojave Desert to Antarctica, and have demonstrated the ability to operate in temperatures as low as minus 211 degrees F (–135 C). Operating at low temperatures without active heating translates into lower power and mass. In tests at UC Berkeley, these rugged microbots have survived drop tests up to 100 feet (30 meters). And researchers are working to extend their current 330-foot (100-meter) range of operations.

With PUFFERs onboard, future rovers would have a greatly expanded range of exploration options with reduced risk. Destinations currently under consideration include Mars and icy moons such as Europa.

PUFFER is being developed in partnership with UC Berkeley, Distant Focus Corp., and Pioneer Circuits, Inc.

A



B

C

**A·** A PUFFER sits adjacent to a Curiosity rover wheel. **B·** Two PUFFERs next to a quarter, fully deployed to the left and folded for transport to the right. **C·** PUFFER prototypes have been tested in a variety of environments, including the Antarctic.

# A VIRTUAL WINDOW ON SPACE

NEW DEVELOPMENTS IN ASTROPHYSICS AND PLANETARY SCIENCE ARE ALWAYS EXCITING, BUT PROVIDING A VISUAL REPRESENTATION TO THE PUBLIC CAN BE DIFFICULT, AND THIS OUTREACH IS A CRITICAL PART OF JPL'S MISSION. JPL-DEVELOPED SOFTWARE BRIDGES THIS GAP BETWEEN TECHNICAL DATA AND VISUAL IMAGERY IN A NEW AND DYNAMIC FASHION.

RANGER IS A THREE-DIMENSIONAL, browser-based visualization system for use by both mission planners and the general public for the visual representation of objects in space. From nearby planets such as Mars, to distant worlds around other stars (such as the recently detected exoplanets in the TRAPPIST-1 system, over 40 light-years away), Ranger allows for online exploration of these other worlds via easily mastered and intuitive manipulation inside a web browser.

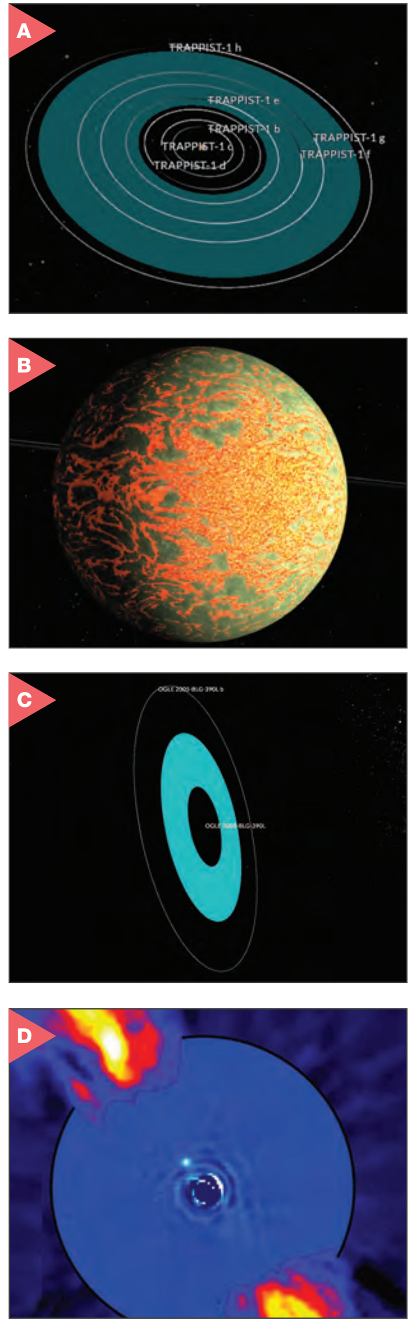
Vast data resources are at the core of Ranger's capabilities: planet sizes, hypothesized surface terrain, atmospheric models, planetary masses, star types, orbits, and more are stored for real-time manipulation by advanced algorithms. While there are artistic impressions included to round out Ranger's presentation capabilities—nobody knows what exoplanets actually look like yet—the software is skewed towards hard data wherever possible, offering the most accurate renditions available.

While the general public can use Ranger to explore the vast reaches of space, it is more than a successful outreach tool. Ranger was derived from software designed to assist engineers and scientists in planning NASA's deep-space missions, and is capable of mission-critical levels of accuracy. It is platform agnostic and can be run on Windows, Macintosh, and Linux machines, as well as tablets and smartphones.

Ranger's core features are continually expanded and improved. Recent additions include a shadow tracker for the upcoming total solar eclipse that will cross North America in August 2017. While most of the data in Ranger comes from NASA, several external institutions are involved in its evolution. For example, researchers at Arizona State University can interact with Ranger as part of their Earth and space science curriculum, adding new data from their own research. The United States Navy has invested in Ranger, with an eye towards visualizing simulated and actual trajectories for autonomous underwater vehicles in challenging environments such as beneath the arctic icecap.

Projects like Ranger offer a compelling connection between NASA's efforts and the general public, as well as an intuitive tool for mission planners.

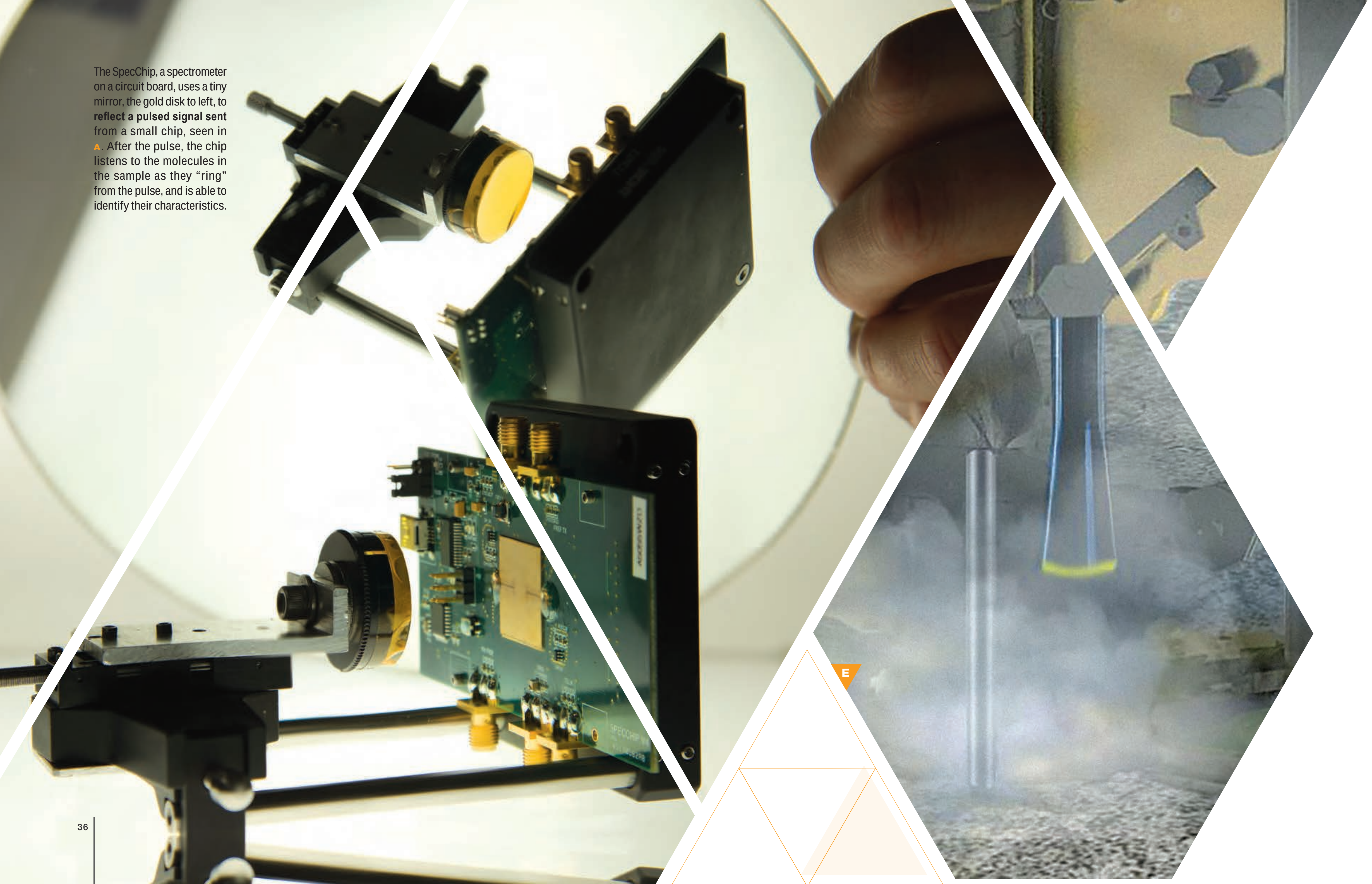
Ranger is a three-dimensional, browser-based visualization system for use by both mission planners and the general public for the visualization of objects in space.



**A-** Ranger software is based on trajectory design algorithms, and offers real-time, configurable views of exoplanetary systems. **B-** While no exoplanets have yet been imaged in detail, Ranger presents artistic impressions based on available data. **C-** Ranger is based on trajectory-planning software. Partnered educational institutions continuously update the data contained within. It is a tool for both ends of the spectrum, from mission planners to the general public. **D-** To complement artistic impressions of distant planetary systems, the best available images from telescopes are associated with their respective stars. This image shows a ring of dust and gas surrounding star Beta Pictoris (credit: ESO).

Ranger is a highly interactive, browser based visualization tool for looking at both distant star systems and Earth. Seen here is a shadow plot for the August 2017 total solar eclipse.

The SpecChip, a spectrometer on a circuit board, uses a tiny mirror, the gold disk to left, to reflect a pulsed signal sent from a small chip, seen in A. After the pulse, the chip listens to the molecules in the sample as they "ring" from the pulse, and is able to identify their characteristics.



# MOLECULAR CHIMES

SPECTROMETERS ARE ESSENTIAL TO SPACE SCIENCE. MOST SPECTROMETERS DETECT HOW LIGHT IS EMITTED, REFLECTED, OR ABSORBED BY SAMPLES TO REVEAL THEIR NATURE. THERE IS ANOTHER TECHNIQUE CALLED ROTATIONAL SPECTROSCOPY THAT MEASURES THE QUANTUM "RING" SPECTRUM OF POLAR MOLECULES IN THE GAS PHASE.

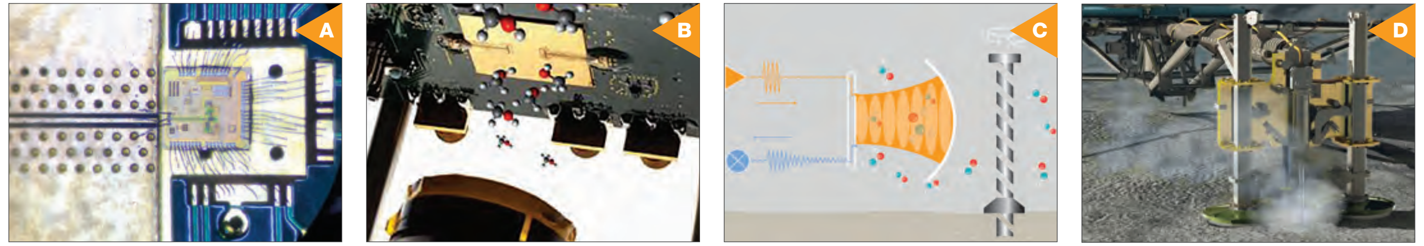
A NEW INSTRUMENT CALLED SPECCHIP uses a technique called pulsed echo rotational spectroscopy to investigate gases in the millimeter wavelengths—the same low-energy radiation used to screen passengers at airport security. To achieve this, the instrument is exposed to a gas, such as the plume resulting from drilling into a comet, which is energized by a short pulse of millimeter-wave energy. This is like a musician striking a bell that causes the molecules in the gas to "ring."Tens of thousands of measurements can be made each second, so very short events can be detected in real time.

By analyzing the spectra gathered after these pulses, researchers can identify specific components of the gas under investigation, including the quantities of each element. This method is able to tell the difference between gas molecules with the same mass, or even the same chemical formula, making it a valuable complement to mass spectrometry.

The SpecChip is ideally suited to missions where traditional spectrometers might have difficulty obtaining samples—it can operate with just a whiff of gas.

The SpecChip technique has been used for research at longer wavelengths for decades, and can now be developed for space applications thanks to electronic chip designs leveraged from the smartphone industry. These chips and associated small optics allow for a compact unit that can operate at high frequencies where the common, lighter gases are observable. The system is a thousand times more efficient than comparable techniques such as cavity ring-down laser absorption. Only about one watt of power is required to operate.

The SpecChip is ideally suited to missions where traditional spectrometers might have difficulty obtaining samples—it can operate with just a whiff of gas. However, it may also be used in conjunction with other spectrometers in more accessible environments. Current development is looking towards operation with a cometary drill, where the SpecChip will be able to hear all of the "bells ringing" in a small, momentary cloud generated during ice drilling.



A- The SpecChip is extremely compact (about one square millimeter) and requires less than a watt of power to operate. B- The SpecChip consists of a pulse emitter, a mirror, and a receiver. The emitter and receiver are both near the gold plate at the top, and the mirror is the round structure at the bottom. C- Gases drifting in front of the SpecChip mirror are energized by pulses of millimeter wave energy. The release of this energy, or echo, is detected shortly afterward and used to quantify the gas mixture. D, E- Mounting the SpecChip near a cometary drill, such as that flown on ESA's Philae lander, exposes it to vapor from the drill-released volatiles. A SpecChip instrument could measure volatile gases in real time to complement other, downstream analyses.

# AIRBORNE AUTONOMY

JPL IS DEVELOPING A FULLY AUTONOMOUS DRONE, CALLED THE MICRO AIR VEHICLE (MAV), THAT WILL HAVE IMPORTANT IMPLICATIONS FOR USE ON EARTH AS WELL AS IN DEEP SPACE THAT COMBINES INERTIAL GUIDANCE, VISUAL TRACKING, RADIO BEACON HOMING, AND GPS TO PROVIDE UNPARALLELED ACCURACY FOR BOTH FLIGHT AND HOMING/LANDING OPERATIONS, CRITICAL TO EXTENDED AUTONOMOUS OPERATIONS.

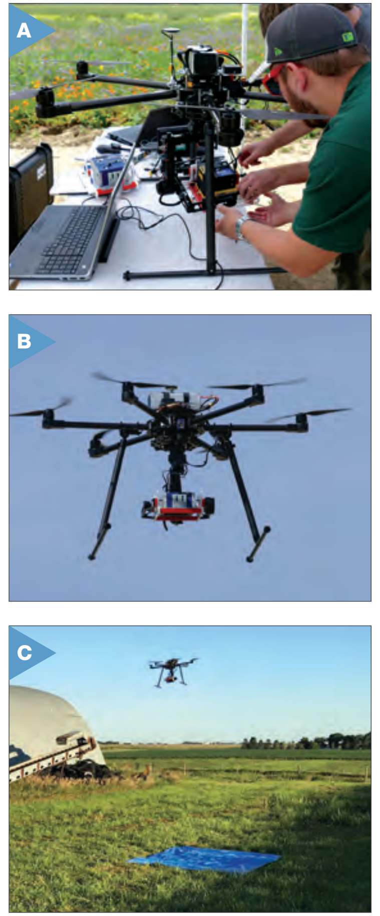
THIS NEW AUTONOMOUS NAVIGATION TECHNOLOGY enables long-duration missions over several days without human interaction, demonstrating a high level of autonomy. Current efforts are focused on developing the MAV for ecosystem monitoring, with high-level and extremely accurate autonomy at its core. Complex, customized algorithms developed at JPL are at the heart of this self-reliant platform.

In its current form, the system is mounted on a commercially available drone carrying an instrument suite that focuses on crop health, critical to agriculture. The MAV can image down to the level of individual leaves, and imaging in the visible and near-infrared provides valuable information on crop hydration and stress levels. Advanced algorithms will allow the data to be used to infer plant nutrient status, the rate of evapotranspiration (plant water use), and even the incidence and severity of diseases. Test flights have been conducted in rural areas and have enabled researchers to examine the health of new crop breeds, or phenotypes, for drought tolerance.

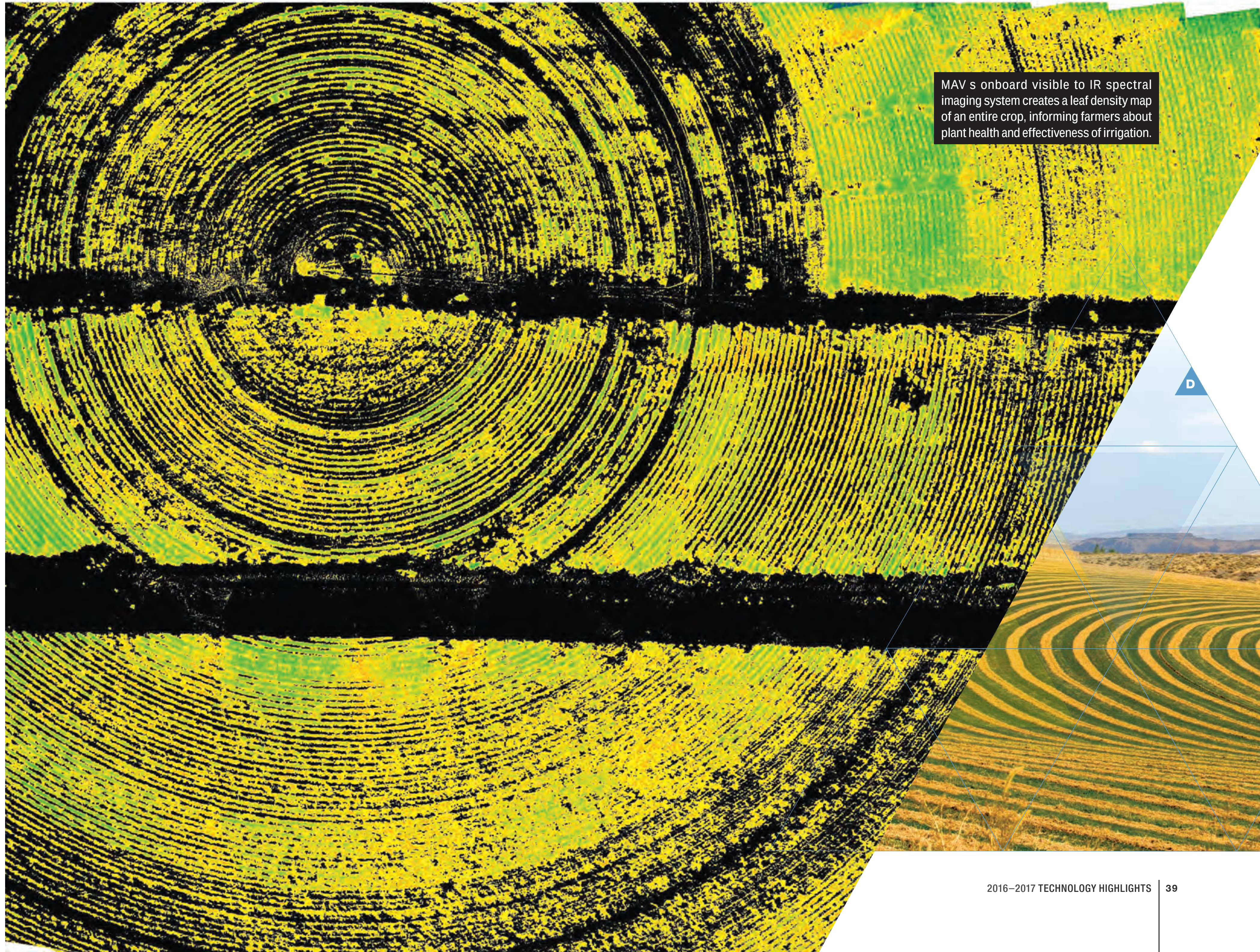
Between sorties the drone is harbored in a charging dock. With a single command, the MAV takes flight, autonomously navigating a selected area with no further human intervention, and recording data relevant to the flight parameters. At the end of its flight, or when it senses that power levels are low, the MAV automatically finds its dock/charging station and lands to download data and recharge its batteries.

The novelty of the MAV navigation system lies in combining multiple navigational tools. It uses its inertial guidance system and GPS for broad navigational tasks, then as it nears its docking station, autonomously searches for visual markers and a radio beacon to calculate the proper maneuvers for landing—a task too exact and demanding to rely on GPS alone. These algorithms will be useful for planetary probes, enabling high levels of autonomy when operating on other worlds where no GPS systems exist. Mars helicopters, icy moon "hoppers," and even underwater applications could benefit from its long-term autonomous abilities.

> With a single command, the MAV takes flight, autonomously navigating and imaging a selected area with no further human intervention.



**A-** Researchers adjust instrumentation before deployment over a crop field. **B-** The MAV is adapted from commercially available quadcopters. Once it reaches the end of a flight, or is nearing battery depletion, it lands at a charging station autonomously. **C-** A MAV takes flight to complete its autonomous circuit of crops. Information is stored onboard for downloading at the completion of its flight. **D-** From high in the air, the MAV autonomously gathers data about plant hydration from the crops below.



MAV s onboard visible to IR spectral imaging system creates a leaf density map of an entire crop, informing farmers about plant health and effectiveness of irrigation.

Future airborne testing will provide data from drones or aircraft, validating wide-scale monitoring of snowpacks. At right is an artist's depiction of a snow radar mounted on a research aircraft.

# RADAR ON A CHIP

RADAR TECHNOLOGY HAS BEEN WIDELY USED FOR DECADES. APPLICATIONS INCLUDE THE DIRECTING OF COMMERCIAL AIR TRAFFIC, MAPPING THE PLANETS IN OUR SOLAR SYSTEM, AND EVEN GUIDING NEW SELF-DRIVING CARS. LEVERAGING THE AGGRESSIVE ADVANCES IN ELECTRONICS DRIVEN BY THE SMARTPHONE INDUSTRY, IT IS NOW POSSIBLE TO BUILD RADARS THAT ARE HUNDREDS OF TIMES SMALLER AND LESS POWER HUNGRY THAN PREVIOUS DESIGNS, ENABLING MANY NEW APPLICATIONS FOR SPACE AND EARTH SCIENCE.

NEW DEVELOPMENTS AT JPL, working in association with the University of California at Los Angeles, have applied the power of these advances in radar technology to the tracking and prediction of drought conditions. A generous snowpack is crucial to maintaining California's water supply. Until recently, snow depth has been measured the same way it had been for hundreds of years—someone walked into the mountains and jammed a stick into the snow, recording how deep it would go. In the past, JPL has measured snow from overflying aircraft with visible-light instruments that revealed details about its surface (color and depth), but not the internal structure—the density of the snow or how melted it was. This limited how accurately the water content could be estimated. The need for information about the internal snow structure presented a problem awaiting a high-tech solution.

JPL's new radar-on-a-chip is a compact and inexpensive radar unit that is small enough to be flown on a commercial drone for automatic measurement of snow's internal structure. As a first step, the radar module has been mounted on a tower at Mammoth Mountain in Northern California for extended testing. From this vantage point, it continually measures snowfall across a season at an accuracy of a few inches. Results from these experiments have been very promising.

The next step will be to mount these tiny radars onto commercial drones for low-altitude measurements of snow over larger areas. Traditional radar instruments, even "miniaturized" ones, are far too bulky and power-hungry to fly on small drones—the new radar-on-a-chip circuitry is smaller than a smartphone and uses only one watt of power, less than a smartphone. The radar transceiver itself is smaller than a pencil eraser.

This remarkable reduction in size and power consumption is made possible by the utilization of advanced CMOS technology and complex semiconductor chips. Despite its small size, the radar chip contains millions of transistors and thousands of subcircuits that perform all the complex signal processing needed for snow measurements—generating and decoding waveforms, converting them between analog and digital formats, and processing these signals to glean information about the snowpack being observed.

In the future, more powerful and increasingly accurate miniature radar devices can be mounted in arrays on planetary spacecraft, CubeSats and nanosats, for example to analyze surface structure on other bodies, using less power, with less mass, and at lower cost.

JPL's new radar-on-a-chip is a compact and inexpensive radar unit that is small enough to be flown on a commercial drone for autonomous measurement of the internal structure of snow fields.

**A**• The entire radar electronics unit is smaller than a smartphone and uses far less power—about one watt. The radar antennas are not shown here. **B**• The radar transceiver itself is smaller than a pencil eraser and is seen at center under a protective plastic bead. **C**• The radar chip was tested high on the snowy slopes of Mammoth Mountain in Northern California, monitoring snow levels and internal structure.

# TRACKINGTHEUNTRACKABLE

A MAJOR CHALLENGE FOR FUTURE PLANETARY EXPLORATION WILL BE TRACKING ROVERS AND OTHER MOBILE INSTRUMENTATION IN CHALLENGING ENVIRONMENTS. MOUNTAINS, CANYONS, OCEANS, AND ICE CAVES CAN ALL WREAK HAVOC WITH RADIO SIGNALS.

SIMILAR PROBLEMS are also encountered by first responders here on Earth when entering concrete buildings or subterranean parking structures where radio and GPS are often ineffective for tracking personnel. New technology developed at JPL allows mobile antennas to be pinpointed to within about a yard (1 m), regardless of their surroundings.

The Precision Outdoor and Indoor Navigation and Tracking for Emergency Responders (POINTER) technology pioneers the use of a small low-power transmitter to generate a quasi-static magnetic field for tracking. Instead of being scattered and absorbed by buildings like radio waves, this field is able to penetrate and bypass these blockages.

But there is more to the story than merely tracking the location of the POINTER unit. Using advanced mathematical algorithms to analyze the emitted fields, tests have demonstrated the ability to not only track POINTER units, but to also discern what orientation they are in, and whether they are moving or stationary. Previous approaches to tracking with quasi-static fields were limited to just a few meters. Researchers at JPL increased the frequencies to improve the signal-to-noise ratio, and developed more robust mathematical algorithms to allow for more precise interpretation of these signals. With these advances, POINTER's effective range has been extended from about 330 feet (100 m) in concrete or rocky environments, to about 2/3 of a mile (about 1 km) through water or inside ice caves.

While POINTER will be important in environments likely to be encountered in planetary exploration, it was originally designed with emergency responders in mind. These personnel have traditionally relied on radio and GPS for communication to coordinate emergency efforts and guarantee their own safety in urban environments. But structures generally composed of concrete, brick, and steel can interfere with radio transmissions, inhibiting communication. This not only slows rescue efforts, but puts the rescuers themselves in danger. The use of POINTER allows first responders to be tracked with high levels of precision in these environments.

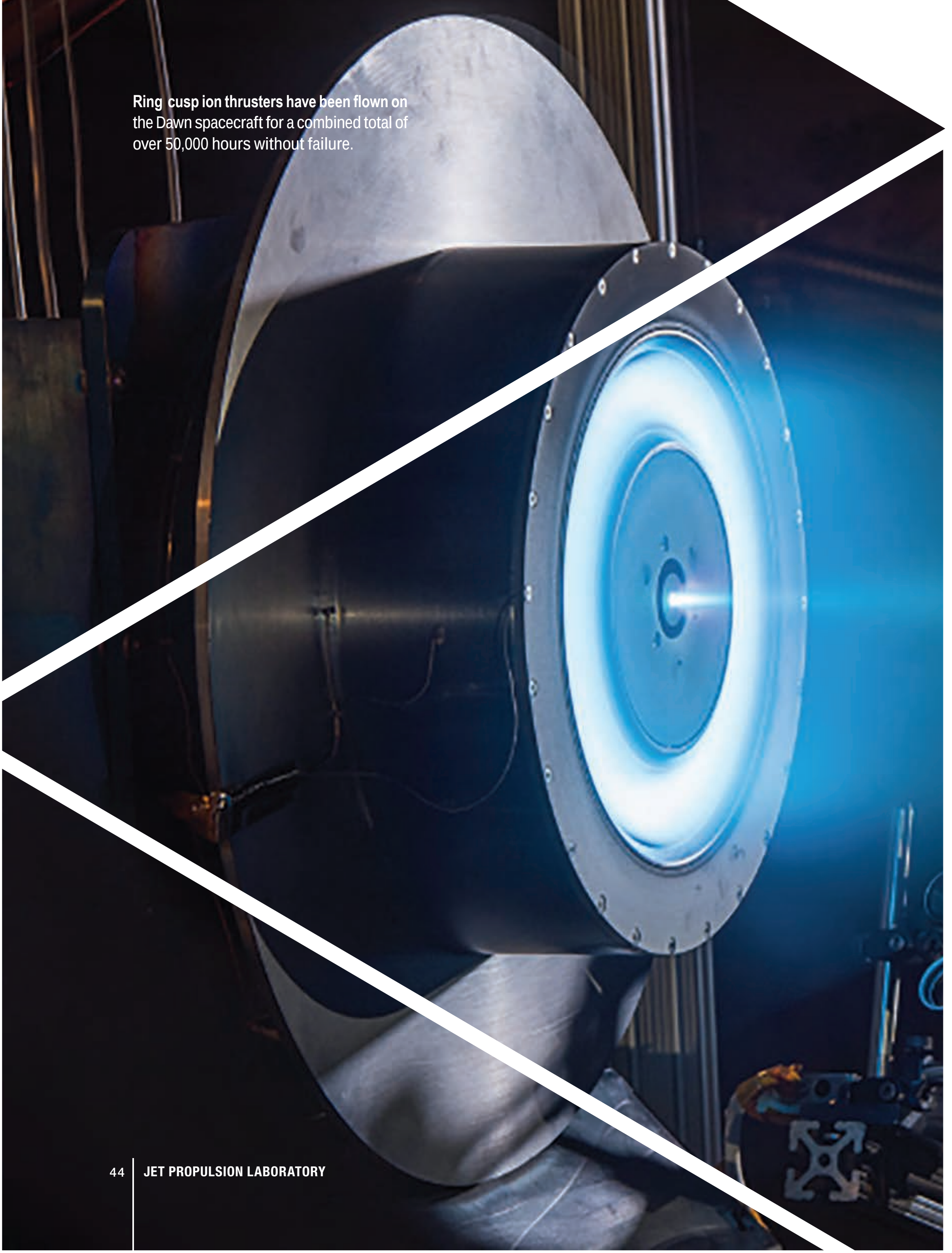
POINTER technology will also open new doors for future space missions. For example, a small rover equipped with POINTER could enter a cave or move below a layer of ice, while staying in continuous contact with a nearby lander that could track its position and orientation. The technology can also be used to create extremely accurate and robust seismometers and accelerometers. POINTER has the potential to enable roving and flying probes to explore the deep recesses and cold oceans of distant worlds with impunity.

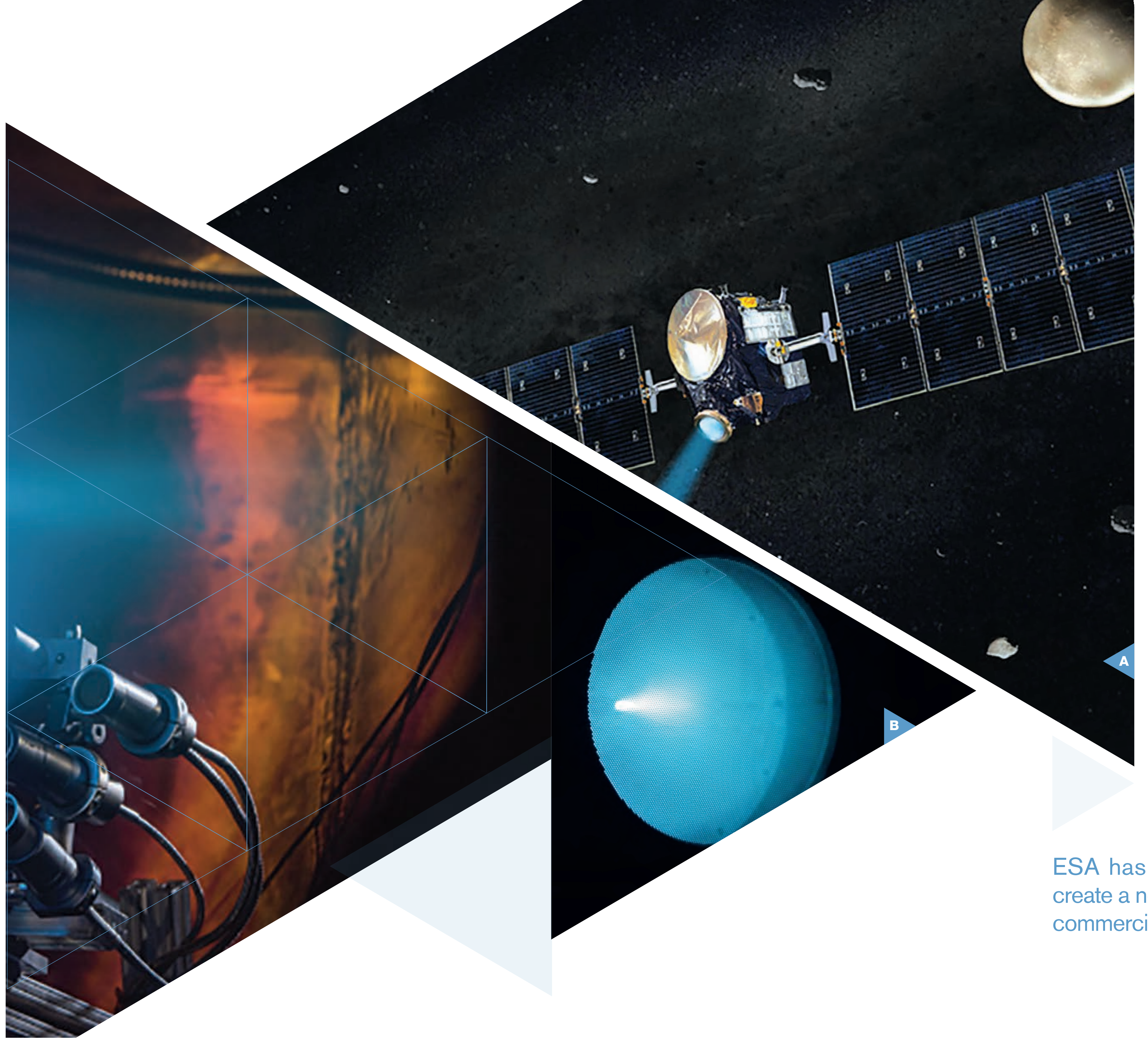
POINTER research and development was supported by the Department of Homeland Security.

> POINTER pioneers the use of quasi-static magnetic fields for precision tracking in urban environments or exploration of deep recesses and cold oceans on distant worlds.

POINTER quasi static fields allow for the tracking of mobile units inside concrete and steel buildings, underwater, or in ice caves, as seen here. This technology will be increasingly useful as we explore the icy worlds of the outer solar system.

A- POINTER was originally designed to track first responders in emergency conditions. The software interface (seen here operating on a laptop in the field) pinpoints not only their location, but also their orientation and rate of movement. B- Unlike cell phones, wireless Internet, radar and GPS, all of which rely on directional radio waves, POINTER antennas use quasi-static magnetic fields for tracking.


Ring cusp ion thrusters have been flown on the Dawn spacecraft for a combined total of over 50,000 hours without failure.



# PERPETUAL GLOW

## ELECTRIC ROCKET TECHNOLOGY DEVELOPED AT JPL IS BEING ADOPTED BY THE EUROPEAN SPACE AGENCY (ESA), AND WILL POWER FUTURE ESA AND NASA MISSIONS TO THE OUTER SOLAR SYSTEM.

**ION THRUSTERS** have been used on robotic spacecraft since 1998, when NASA's Deep Space 1 (DS-1) mission was launched to investigate an asteroid and a comet, and to prove that ion thrusters could work over extended periods in space. Further proof of the longevity of this NSTAR ion engine came from the Dawn mission to the asteroid belt, which has accumulated over 50,000 hours of combined ion thruster operation.

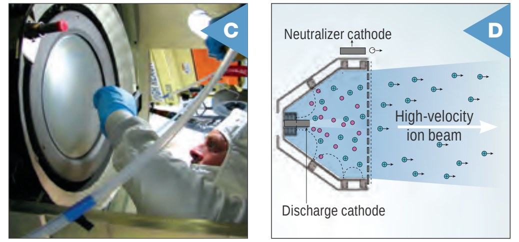
Ion thrusters inject a neutral gas (usually xenon) into the engine's chamber, where an electron discharge is passed through the gas to produce ions that are accelerated and thrust out into space to create a propulsive force. Over a hundred ion thrusters have been successfully flown to date.

While ion thrusters have much less thrust than chemical rockets, they have much higher specific impulse and efficiency, so an ion engine requires much less propellant for deep-space missions. They can fire for extended periods of time, continuously accelerating the spacecraft to cross vast distances. Ion thrusters can also be "parked" for years between firings with no ill effects. These traits make them ideal for in-space propulsion on long-duration missions.

Research at JPL has led to improvements in ion thruster design, with the ring-cusp ion thruster being one of the most impressive advances. Earlier designs, called Kaufman thrusters, used baffles in the discharge chamber that eroded over time. JPL's ring-cusp ion thruster design greatly enhances performance by eliminating baffles and surrounding the chamber with permanent magnets, which confine the electron flow inside the engine and increase its efficiency to up to 80 percent over Kaufman designs. The result is much longer engine life with less loss of thrust over time.

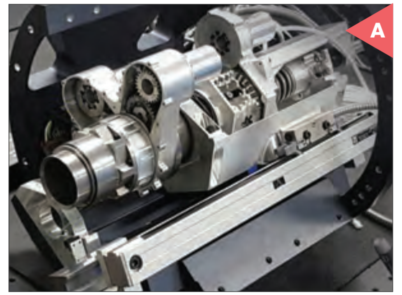
The European Space Agency (ESA) has used Kaufman thrusters for decades, but is ready to embrace the ring-cusp design for future planetary missions. ESA has engaged JPL designers to help create a new thruster to be manufactured by a commercial European provider. Modeling and design support work for this thruster is currently underway at JPL, where it will be validated once a working prototype is produced by ESA. This partnership between JPL, ESA, and industry will provide an engine of sufficient power and longevity to not only fulfill ESA's needs, but also power NASA's future Discovery-class missions

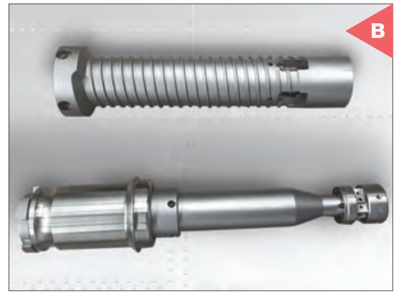
ESA has engaged JPL designers to help create a new thruster to be manufactured by a commercial European provider.

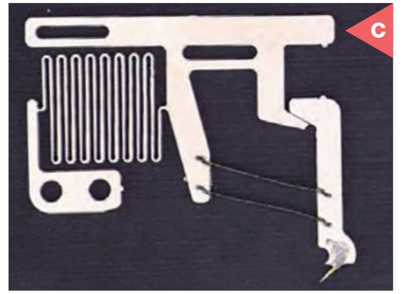


**A** • The DAWN mission was propelled by an NSTAR ion thruster. **B** • NSTAR ion thruster discharge. **C** • NSTAR ion thrusters on NASA's Dawn spacecraft being readied for launch. **D** • Diagram of ion ring-cusp ion thruster.

# ASTEROID ANCHORS







The Microspine Gripper and Anchoring Drill will provide a rock-steady attachment-point for spacecraft visiting low-gravity objects.

WHEN SPACE EXPLORERS, EITHER HUMAN OR ROBOTIC, REACH A LOW-GRAVITY OBJECT IN DEEP SPACE, THEY WILL NEED TO ANCHOR THEMSELVES TO ITS SURFACE TO SUCCESSFULLY CONDUCT OPERATIONS THERE. NEW TECHNOLOGY BEING PROTOTYPED AT JPL PROVIDES THE ABILITY TO GRIP THE SURFACE OF A SMALL BODY AND INSERT A STRONG, STABLE, AND PERMANENT ANCHOR.

**JPL'S MICROSPINE GRIPPER AND ANCHORING DRILL** will provide a rock-steady attachment point for spacecraft visiting low-gravity objects. The gripper consists of a ring of jointed metallic fingers with dozens of sharp spines at their tips that conform to the rough surface of rock or gravel and can grip small bumps, pits, and other irregularities in the surface.

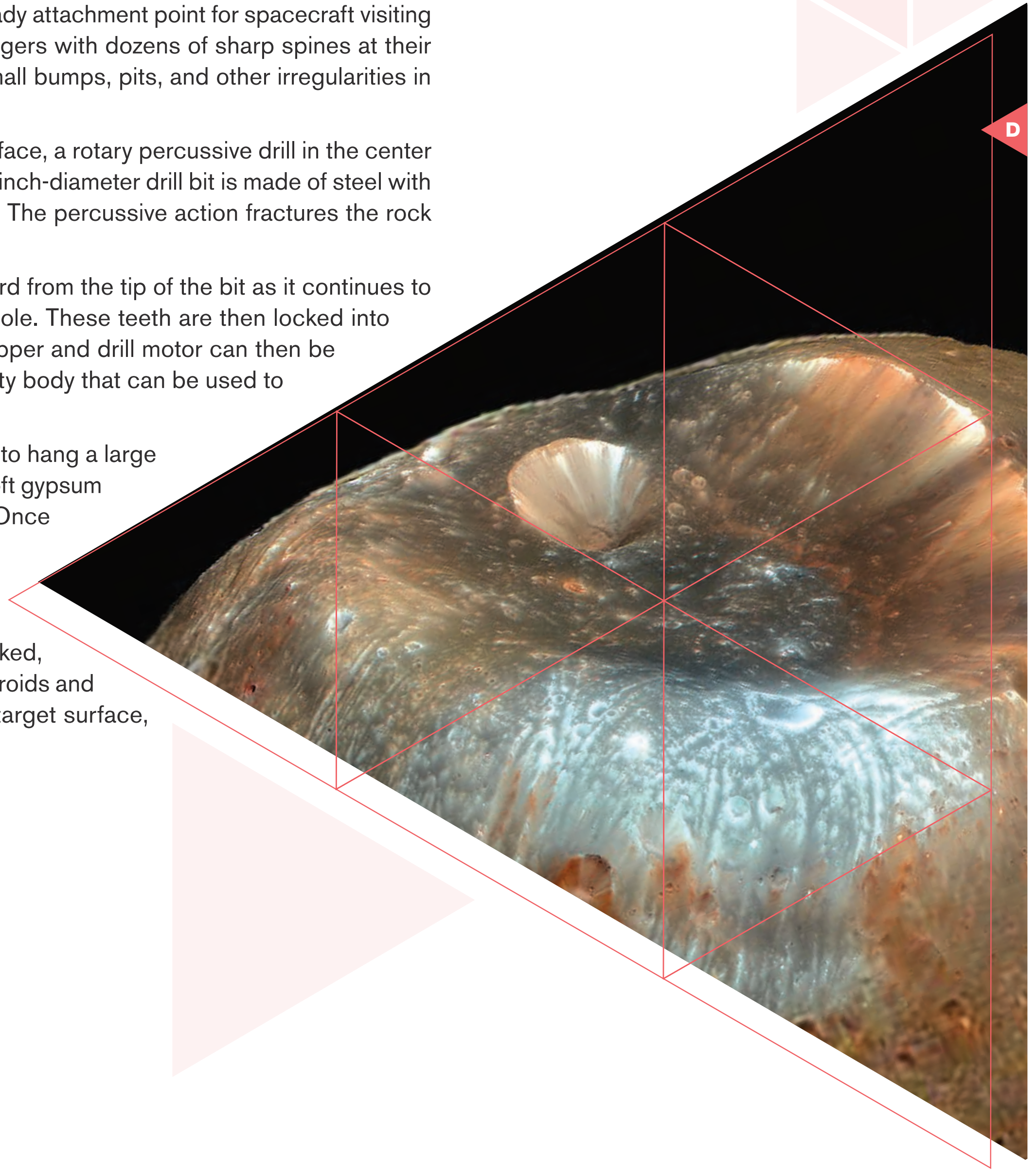
Once the gripper has temporarily planted itself firmly onto the target surface, a rotary percussive drill in the center of the ring-shaped structure is driven into the rock or ice below. The one-inch-diameter drill bit is made of steel with carbide "teeth," and can cut through even the hardest rock anticipated. The percussive action fractures the rock debris, which is removed during rotation.

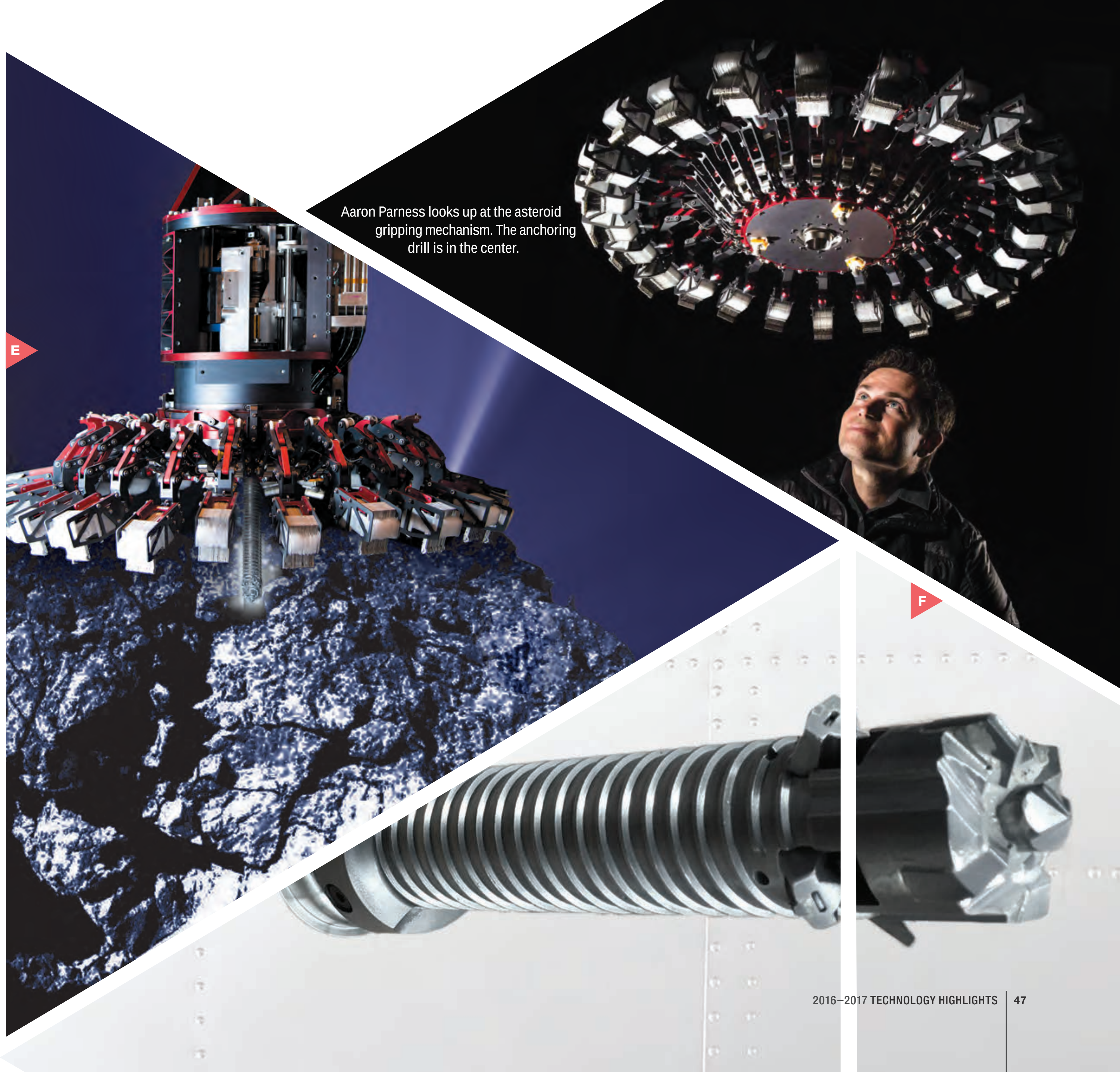
After the drill reaches its full depth, additional carbide teeth pivot outward from the tip of the bit as it continues to spin, cutting a ¼-inch (6.3-mm) wider void at the bottom of the bore hole. These teeth are then locked into position, anchoring the drill bit into the rock or ice. The ring-shaped gripper and drill motor can then be removed, leaving a shaft that extends above the surface of the low-gravity body that can be used to anchor another spacecraft or component.

A good terrestrial analogy would be toggle or molly bolts one might use to hang a large picture or heavy flatscreen television. Modern interior walls are made of soft gypsum board through which one can drill a hole and insert one of these bolts. Once the bolt extends through the wall, the tips expand, gripping the far side. They are almost impossible to remove once installed, but for anchoring to an asteroid or comet, this is a desired characteristic.

This technology has been tested on hard and soft surfaces, and in cracked, crumbly, and unstable rock—all typical of low-gravity objects such as asteroids and comets. In each case, it was effective in grasping and drilling into the target surface, providing a rock-solid, anchored grip.

**A·** The anchoring drill mechanism uses a percussive drive to bore into the rock—hardness can vary from crumbly talc to hard stone—then switches to purely rotary motion to grind out the anchoring groove. **B·** Components of the asteroid anchoring drill. At top is the drill body, with cutouts for the anchoring teeth at the right. At bottom is the inner mechanism, which contains the configurable anchoring teeth. **C·** Seen here is a single microspine, which will be assembled into a cassette of 20. Multiple cassettes are used in the asteroid gripper. **D·** In addition to asteroids and comets, moons such as Phobos are sufficiently low-gravity that working on their surface will require a permanent anchoring device. **E·** Once the microspine gripper has firmly grasped the surface of a low-gravity object, the drill (at center of image) bores into the rock or ice, then permanently anchors itself with carbide teeth. **F·** The drill moves through the rock or ice with both percussive and rotary action, then once deep inside, carbide teeth swing out to cut a wider channel. In this configuration, these teeth anchor the drill bit into the object.





Aaron Parness looks up at the asteroid gripping mechanism. The anchoring drill is in the center.

As part of a project to improve energy pipeline industry safety, a miniature robotic drone carrying JPL's Open Path Laser Spectrometer enables methane detection with higher sensitivity than previously possible.

# LEAKSENTRY

DETECTING METHANE LOCALLY AND IN SMALL CONCENTRATIONS IS CRITICAL TO A BETTER UNDERSTANDING OF CLIMATE CHANGE AND BOTH INDUSTRIAL AND NATURAL EMISSIONS. NEW MINIATURIZED SPECTROMETERS BEING DEVELOPED AT JPL PROMISE TO REVOLUTIONIZE HOW THIS POTENTIALLY DANGEROUS GAS IS DETECTED ON EARTH WITH SMALL AND HIGHLY SENSITIVE INSTRUMENTATION.

**AMAZING DISCOVERIES** have come from the Tunable Laser Spectrometer (TLS) aboard the Curiosity Mars rover since it landed in August 2012. Among these was the detection of methane on the Martian surface. The TLS is a remarkable instrument, and in the years since its deployment, JPL has made great strides towards smaller, more sensitive, and more robust tunable laser spectrometers with expanded capabilities that can also be applied on Earth for detecting pollution, increasing public safety, and monitoring greenhouse gas levels.

JPL's Open Path Laser Spectrometer (OPLS) is small enough to be carried on miniature robotic drones, and can detect leaks from nearly 1000 feet (over 300 m) away. The instrumentation was miniaturized and ruggedized to fly on small aerial drones without sacrificing sensitivity. The software was modified in order to run on small, off-the-shelf processors such as those found in smartphones. The entire system is intended for continuous, semi-autonomous operation. This technology, pioneered at JPL, uses proprietary algorithms to drive a unique combination of custom-built and off-the-shelf components.

These small, drone-carried spectrometers will allow for real-time monitoring of natural gas infrastructure such as pipelines, drilling and pumping stations, and other facilities that are currently surveyed using bulky instruments carried on aircraft or automobiles. While existing instruments are capable of spotting large leaks, they are expensive, heavy, and require skilled operators. As a result, many production and distribution facilities are checked as infrequently as once per year.

The use of small drone-mounted spectrometers will allow for better monitoring of long stretches of pipeline. Because the sensors themselves are much less expensive than existing units, they can be permanently installed in high-risk areas. This technology will also allow scientists to monitor other emission sources such as volcanoes and swamps resulting from permafrost melts. These miniature spectrometers are so sensitive that even with Earth's average methane level at about 2 parts per million, an increase of just a fraction of a percent can be detected. Ongoing research will allow these sensors to detect a broader range of environmentally dangerous gases at ever smaller concentrations.

OPLS was developed in partnership with the Pipeline Research Council International (PRCI).

These miniature spectrometers are so sensitive that even with Earth's average methane level at about 2 parts per million, an increase of just a fraction of a percent can be detected.

A• Methane plumes are invisible to the naked eye, but are detectable up to hundreds of meters away by a TLS instrument. Small sensors like the OPLS would be ideal for providing early warning prior to massive releases such as the Aliso Canyon methane leak seen here in an infrared image.

# BIRTH OF THE ELEMENTS

## SOME OF THE BEST SCIENCE HAS ITS ROOTS IN A MOMENT OF SERENDIPITY, AND THIS WAS THE CASE FOR A NEW QUANTUM CAPACITANCE DETECTOR DEVELOPED AT JPL.

**A FEW YEARS BACK**, a team of engineers were working on a quantum computing project, an area that promises to revolutionize data handling for many kinds of problems that can bog down today's computing systems. This project utilized Cooper pairs, two electrons bound together in the superconducting state, that are used in advanced computing in a manner similar to the 1 and 0 bits used in traditional computing.

But there was a problem. Small electromagnetic fluctuations in the system would cause the bonds between the Cooper pairs to break. While pondering this, JPL researchers realized that this phenomenon could actually be useful if reversed—the device could be used to measure tiny amounts of radiation that had caused the Cooper pairs to break—and do so with incredible accuracy. While this kind of detector could ultimately be made to work with almost any type of electromagnetic radiation, the team decided to concentrate on far-infrared (far-IR) radiation, which although of particular value to astronomers has not benefited to date from commercial or military investment.

The far-IR is critical to understanding the formation and evolution of galaxies from their very beginnings because it allows astronomers to "see" through dust that infuses the galaxy and is opaque to other forms of visual observation. In particular, within about a billion years of the Big Bang, newly forming stars in small young galaxies created the first elements heavier than lithium, including carbon, oxygen, and nitrogen. These "heavy elements" set the stage for the eventual chemical richness of planetary systems and, in the case of Earth, life. They also have spectral signatures in the far-IR, which is unobscured by dust and thus enables a pristine view of elemental origins and galactic formation between 500 million years after the Big Bang to the present.

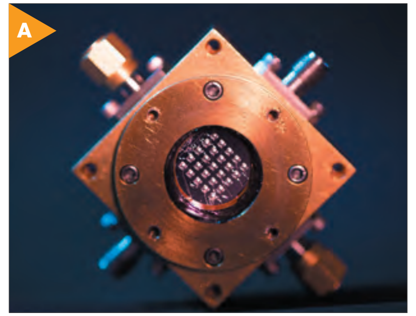
However, sensitive observations in the far-IR are very challenging. Seeing galaxy formation requires both a cold space telescope and very sensitive detectors. Unlike in the optical and near-IR, astronomers working in far-IR must develop their own detector technology. The small photon energies and extreme sensitivity required mean that even getting a single detector pixel at the target sensitivity is a major technical hurdle. Building and reading out large arrays that can be used in a space mission is an added challenge.

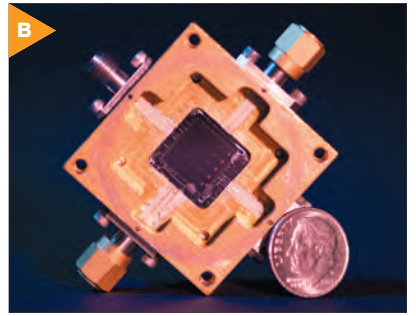
The Quantum Capacitance Detector may be the solution. It has demonstrated the required sensitivity astronomers are seeking for future far-IR missions, and is capable of detecting individual far-IR photons. The detector arrays use a mesh of tiny wires—about 50 nanometers wide, or 1/1000 the diameter of a human hair—to collect these incredibly faint signals. They then transform the impacts of single photons into a signal that may help to answer questions about the very origins of the universe.

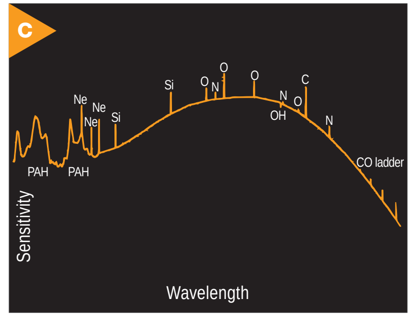
> The Quantum Capacitance Detector is capable of detecting individual far-IR photons.

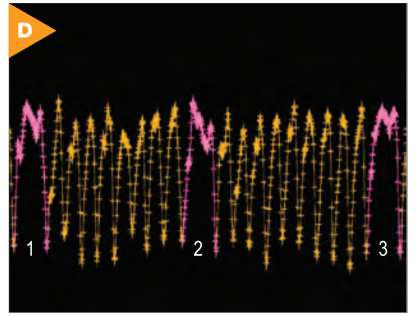
**A-** An e-beam-written Fresnel lens array designed to focus radiation on the detector. **B-** Quantum capacitance detector array. **C-** Mid- to far-IR spectrum of a galaxy showing heavy elements and signatures of carbon and oxygen, as well as dust that might be observed in the early universe with a future far-infrared space observatory. **D-** Quantum capacitance signal displaying missing peaks (purple) due to absorption of a single photon.


JPL's Quantum Capacitance Detector, when mounted on a space telescope, will be able to measure individual infrared photons from the earliest moments of galactic formation.









The vortex mask completely extinguishes light from an on-axis point source, allowing imaging of nearby off-axis targets. The phase modulation of the vortex mask is visible only by **looking at it between two polarized filters.**

# A BILLION TO ONE

ONE OF THE TRICKIEST PARTS OF SEEING PLANETS ORBITING OTHER STARS IS BLOCKING THE LIGHT FROM THE HOST STAR. THAT'S WHAT A CORONAGRAPH DOES—IT BLOCKS STARLIGHT, ALLOWING US TO SEE FAINT, NEARBY OBJECTS SUCH AS LARGE EXOPLANETS AND DUST DISKS.

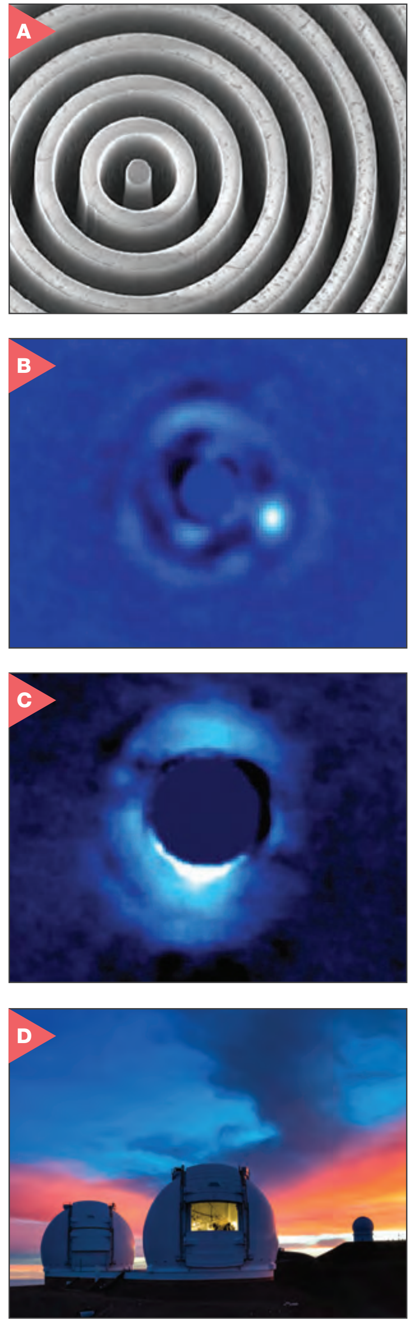
THIS WAS TRADITIONALLY DONE with a simple occluding mask. Unfortunately, this approach also blocks light from nearby objects such as exoplanets orbiting close to the host star. A different design is needed to see such objects, and one answer is the vortex coronagraph being developed at JPL and Caltech.

Rather than using an opaque mask to block starlight, the vortex coronagraph utilizes a phase mask that adds a very specific time delay pattern to the arriving stellar light, redirecting the light away from the detectors using a technique in which light waves are combined and canceled out. This can be done with a pattern of bullseye-like concentric rings just a few microns wide, etched onto a tiny synthetic diamond wafer, or by using similarly oriented liquid crystal molecules. This allows the dim exoplanet light—about a billionth as bright as the light from the host star—to be imaged. The effectiveness of this process has been compared to masking the image from a lighthouse to see a nearby firefly.

The vortex coronagraph has been tested on several terrestrial telescopes, including the 200-inch at Palomar Observatory and the Keck Observatory in Hawaii. Its ability to image objects closer to their host stars than any previous instrument was demonstrated by the very first images of close-in exoplanets and detections of dusty rings around a star that may one day form a planet. The first direct image of a brown dwarf separated by only 23 astronomical units distant from its parent star was also achieved using a vortex coronagraph. One of the advantages of this instrument is that it can see closer to host stars than traditional coronagraphs. Vortex coronagraphs can also be utilized in smaller telescopic apertures, making the design an ideal candidate for space telescopes.

Future potential observations for the vortex coronagraph include seeking young planetary systems, especially those near the "frost-line," with orbits that allow a planet to be cold enough so that volatiles such as water, methane, and carbon dioxide can condense. This region is thought to divide rocky inner planets from gas giants farther out. This instrument will also allow the observation of gas giants close to their host stars, such as "hot Jupiters," and help us understand whether they form far from the star and migrate inward, or are born near the star and head into more distant orbits. Answering these and other questions is an important step toward understanding how solar systems form.

> What makes the vortex coronagraph unique is that it does not block the starlight with a mask, but instead redirects light away from the detectors using a technique in which light waves are combined and canceled out.



**A**▪ Viewed with a scanning electron microscope, the "vortex" microstructure of the mask is revealed [Image credit: University of Liège/ Uppsala University]. **B**▪ A brown dwarf star, located 23 times as far from its host star as Earth is from the sun, is seen here to the right of center. **C**▪ The dusty disk of planetary material surrounding a young star, located 380 light-years away from Earth, can be seen surrounding the center, which has been darkened by the vortex mask. **D**▪ The vortex coronagraph has been tested at the W.M. Keck Observatory in Hawaii, where it enabled the imaging of the brown dwarf star shown above in **B**.

# LEGOS® IN SPACE

AUTONOMOUS ASSEMBLY OF STRUCTURES IN SPACE WILL TRANSFORM ROBOTIC AND HUMAN SPACEFLIGHT. TO DATE, LARGE-SCALE ORBITAL ASSEMBLY HAS BEEN LIMITED TO THE INTERNATIONAL SPACE STATION, A LABORIOUS AND DANGEROUS TASK. NEW AUTONOMOUS ROBOTIC ASSEMBLY TECHNIQUES BEING DEVELOPED AT JPL PROMISE TO TRANSFORM THIS PROCESS.

USING AUTONOMOUS ROBOTICS as an enabling technology, JPL has developed a new design for scalable in-space assembly of large structures. The system uses modular components that are robotically deployed and assembled in space. This approach overcomes limitations imposed by launch fairing diameters, enables large system development in phases, reduces overall system complexity, facilitates repair and replenishment of components, and offers enhanced economy.

Of the many types of spacecraft that will benefit from in-space assembly, orbiting telescopes are an obvious near-term choice. The James Webb Space Telescope (JWST) will launch in 2018, carrying an unfolding mirror over 21 feet (6.5 m) in diameter. But telescopes larger than this will have to be assembled in segments, and that's where autonomous robotic assembly comes into play.

A conceptual design envisions a telescope of about 328 feet (100 m) in diameter. It would utilize modular deployable components that, once assembled, form a support structure for the mirror. The mirrors would then be affixed to this framework as modular elements. The process resembles a LEGO-like construction technique that should result in great versatility for a variety of missions. The individual mirror support modules resemble a fistful of pencils when collapsed for launch. These struts are hinged at opposing ends, and when expanded, form a rigid structural element. Upon arrival in space, the multipurpose robot is activated, and then unfolds and assembles the modules autonomously.

As a first step, JPL has demonstrated an autonomous robot that utilizes repeated, rapid assembly of prototypical space-deployable structures. A prototype 3-meter truss was successfully constructed from modular components. Assembly was iterated multiple times with no failures while maintaining subcentimeter-level accuracy. The robot and its assembly techniques are standardized, and once proven in space will be useful for a wide variety of hardware construction. Cislunar research stations, fuel depots, and lunar habitats are just some of the possible long-term applications. This project was developed with funding assistance from DARPA.

Using autonomous robotics as an enabling technology, JPL has developed a new design for scalable in-space assembly of large systems.

**A,B-** Once a space telescope framework has been assembled, the mirror segments are attached to complete the instrument. The robot is intended to be a general-purpose assembly machine, useful for a variety of modular mission designs.

In-lab tests of the autonomous robot demonstrated repeatable, rapid assembly of a 3-meter truss. This test was completed in under 26 minutes without errors.

The Very Long Baseline Array, or VLBA, uses radio telescope antennas in locations throughout the United States, and is able to draw additional data from other antennas in Germany and Puerto Rico. *CREDIT: Danielle Futselaar / Jason W.T. Hessels - ASTRON*

To examine the vast amounts of data retrieved, V-FASTR utilizes a machine learning classifier, which is trained to recognize and set aside signals from "curious things" in space.

# CURIOUS THINGS IN SPACE

FRBS, OR FAST RADIO BURSTS, WERE FIRST NOTICED IN 2007, WHEN AN ODD BURST OF ENERGY FROM THE SKY–THE BRIGHTEST RADIO OBJECT VISIBLE AT THAT MOMENT –EMITTED AS MUCH ENERGY IN FIVE MILLISECONDS AS OUR SUN DOES IN A MONTH. ASTRONOMERS WERE PUZZLED–WHAT WAS IT?

THIS WAS THE GENESIS of one of the most perplexing questions in modern astronomy: the secrets behind FRBs. While it is hypothesized that many thousands of these transient bursts may occur each day, their timing and source locations are unpredictable, and thus go largely unobserved. Theories about FRB origins range from neutron stars colliding with comets to evaporating black holes. The problem is that we have little observational data with which to find the answer. Compounding this conundrum is that time on radio telescopes is limited, and the chances of finding an FRB by aiming a dish at a limited area of the sky are small. JPL is pursuing a new way to address this vexing astronomical puzzle.

The V-FASTR (VLBA Fast Transients) project analyzes data collected by the Very Large Baseline Array (VLBA), a network of radio telescopes, to search for FRBs. The VLBA is a complex of 10 parabolic radio dishes controlled from Socorro, New Mexico, but spread across the northern hemisphere.

At the core of the project are JPL-designed algorithms that parse the vast amount of data recorded by the VLBA every day, looking for outlier signals that might be FRBs. VLBA observations are recorded on an array of one-terabyte hard drives, which are shipped daily via FedEx to the New Mexico operations center–the data are too massive to be sent via the Internet. To examine the vast amounts of data retrieved, V-FASTR utilizes a machine learning classifier, which is trained to recognize and set aside signals from pulsars and interference from human-created sources such as aircraft and satellites. The use of an array of radio dishes allows V-FASTR to compare possible detections from different sources–four or more stations must detect the same burst for it to be classified as a potential FRB.

Since 2014, V-FASTR has found nearly 100,000 artifacts and 22,000 pulsar signals. The ever-expanding archive of interesting–but as yet, unexplained–signals is called, simply, "curious things." Over time these should help to explain the root cause of FRBs.

V-FASTR is a critical tool for finding and understanding the mysterious FRBs. Future possibilities include the integration of advanced machine learning. Also under consideration is scaling the software to accommodate other radio telescope arrays, such as the Square Kilometre Array that is scheduled to begin operations in 2020, to increase V-FASTR's reach. V-FASTR–style algorithms will continue an expanded search 24/7 as a "free ride" off existing observation programs.

**A-** A partial days' worth of data from one of 10 VLBA telescopes is shipped overnight to Socorro, New Mexico, for processing using a removable data module. Each data module contains eight hard drives and almost one terabyte of data. **B-** The VLBA correlator that runs the V-FASTR software includes 20 PCs, each with four core processors. **C-** One of the 10 VLBA radio telescopes that work together as an array that forms the longest interferometry system in the world, operated by the National Radio Astronomy Observatory. **D-** Example V-FASTR candidate with signal strength as a function of frequency (in MHz) and time. Vertical red lines indicate the start and end of the event. "Before," "during," and "after" regions are used to calculate descriptive features. **E-** The VLBA has radio telescope antennas in various locations throughout the United States and is able to draw additional data from other antennas in Germany and Puerto Rico.

# REDROCKRETURN

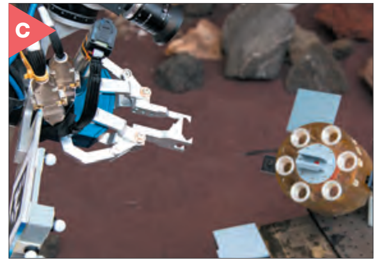
A MARS SAMPLE RETURN HAS BEEN IDENTIFIED AS A HIGH PRIORITY BY SCIENTISTS. A KEY CHALLENGE FOR A POSSIBLE FUTURE RETRIEVAL MISSION WOULD BE TO COLLECT THE SAMPLES CACHED BY MARS 2020 OR OTHER FUTURE ROVERS. TO REDUCE THE RISK TO THESE PRECIOUS SAMPLES, THEIR ACQUISITION AND TRANSFER TO THE RETURN VEHICLE WOULD REQUIRE ROBOTS WITH ENHANCED DEXTERITY, OPERATED BY AUTONOMOUS SOFTWARE.

WITH THIS CHALLENGE IN MIND, THE MARS 2020 sample caching must be designed to be compatible with a future retrieval system. As the 2020 rover progresses across the Red Planet, it will be depositing core samples drilled from the surface, and enclosed in small metal tubes about the size of a cigar, at carefully recorded locations for possible recovery by a later mission. However, during the years between the caching and potential retrieval missions the sample environment may evolve in unpredictable ways. Consequently, retrieving these samples is a task that requires careful grasping techniques and autonomy, neither of which have yet been tested on distant worlds.

A team at JPL has been testing new approaches to execute the retrieval process and assure compatibility with the caching system. When and if the retrieval rover reaches Mars, many years will likely have passed since the Mars 2020 samples were cached. Some may be partially buried, some may have rolled next to a rock or into a crevice, and some may have been deliberately placed under a rocky overhang to shield them from radiation exposure and temperature gradients.

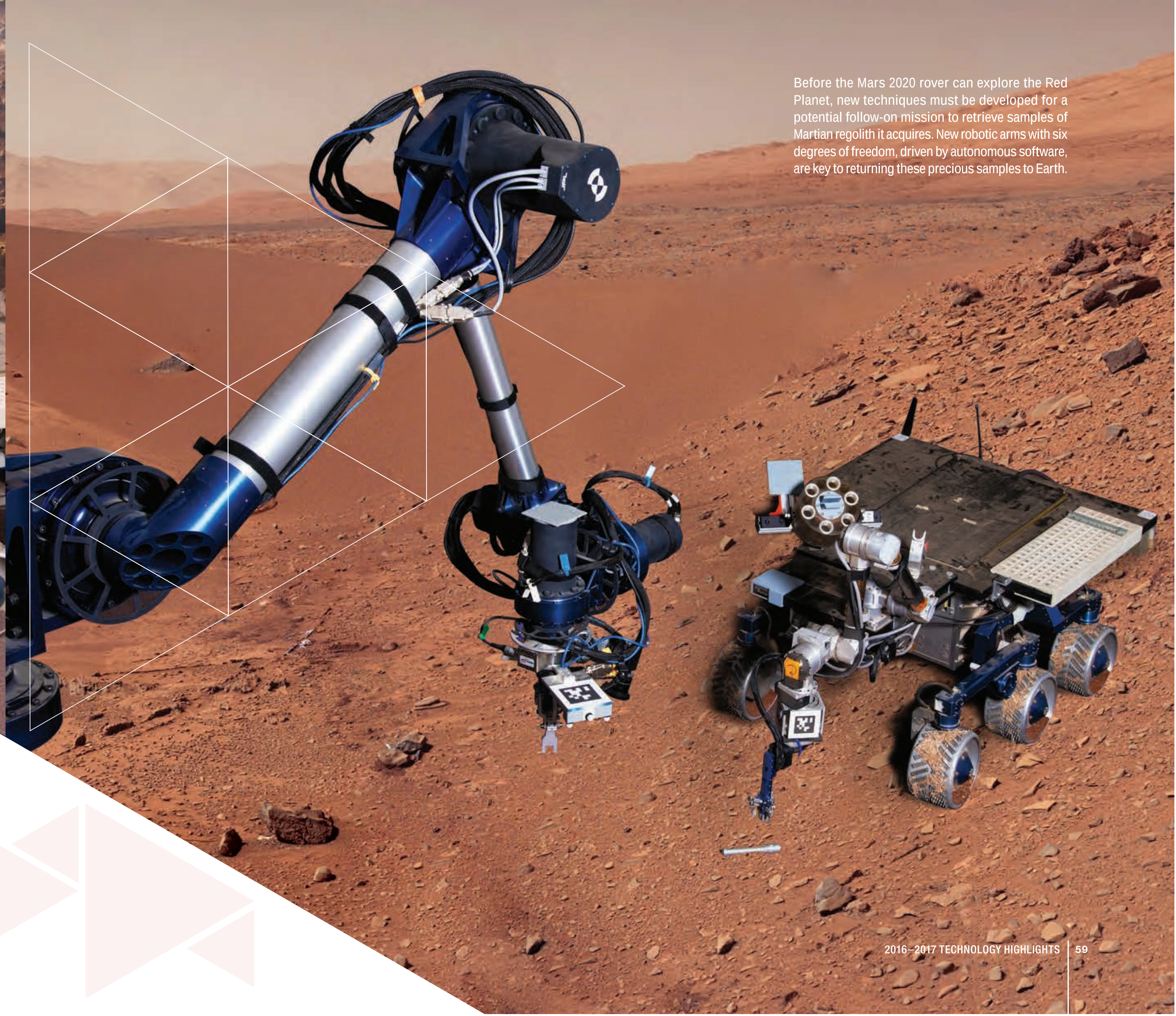
The team has considered a multitude of variables to lead to successful recovery in any conceivable scenario. This has led to the design, construction, and testing of a suite of new robotic devices that have been thoroughly tested in laboratory settings as well as in JPL's Mars Yard. The most obvious of these is the robotic hand that would grasp sample tubes. This three-jawed device grabs the tube radially near one end. Feedback from the gripper tells the onboard computer when enough force has been exerted to assure a secure grip on the sample tube—too much pressure might crush it, and too little could allow the tube to slip free.

This gripper would at the end of a long robotic arm with six degrees of freedom. This allows the gripper to conduct complex operations for sample tube acquisition, processing, and loading the sample tube onto a Mars Ascent Vehicle for orbital rendezvous with an Earth Return Vehicle. This mission would require autonomous control software for obstacle avoidance while driving, sample tube detection, localization, collection, and processing of the tubes. This would greatly reduce the primary mission duration and lower risk. Given the complexity of the task, and the communication delay from Mars, remote operation from Earth is impractical and makes autonomy a necessity. The more self-reliant the machine can be, the better. Once Martian surface samples have been returned to Earth and are available for analysis in the lab, we may learn more about Mars in a few months than we have during the past 60 years of exploration.



While a sample return mission may be 10 or more years in the future, we must understand how it could be accomplished now, before the Mars 2020 rover design is finalized.

**A**· Principal Investigator Eric Kulczycki demonstrates an enhanced robotic claw, designed to grasp Mars core samples cached by the Mars 2020 rover. **B**· Autonomous software guides the effector by a fetch rover in this simulation of core sample retrieval. **C**· Once the sample tubes have been recovered by the fetch rover, they would be placed inside the circular container at right center, then transferred to the Mars Ascent Vehicle.



Before the Mars 2020 rover can explore the Red Planet, new techniques must be developed for a potential follow-on mission to retrieve samples of Martian regolith it acquires. New robotic arms with six degrees of freedom, driven by autonomous software, are key to returning these precious samples to Earth.

**AVIRIS-NG undergoing final** alignment in the laboratory with the telescope, spectrometer, detector array, and onboard calibration mechanisms fully integrated.

# FROM CALIFORNIA TO THE BAY OF BENGAL

ADVANCED IMAGING SPECTROSCOPY TECHNOLOGY DEVELOPED AT JPL IS ENABLING NEW APPROACHES TO MEASURE A RANGE OF EARTH ENVIRONMENTS. IN THE PAST, GATHERING DATA FROM DIVERSE ENVIRONMENTS REQUIRED MULTIPLE INSTRUMENTS, EACH COVERING LIMITED RANGES OF THE SPECTRUM. JPL'S AIRBORNE VISIBLE/INFRARED IMAGING SPECTROMETER NEXT GENERATION (AVIRIS-NG) COMBINES THESE CAPABILITIES INTO A SINGLE INSTRUMENT WITH ENHANCED SENSITIVITY AND SPECTRAL RANGE, WHILE REDUCING SIZE, MASS AND POWER REQUIREMENTS.

**FOLLOWING MORE THAN TWO DECADES** of successful operations by the original AVIRIS instrument, AVIRIS-NG measures the continuous spectrum from the visible to the short-wavelength infrared with fine (5 nanometer) spectral sampling. The ground resolution can be as small as 12 inches (0.3 m), offering access to finer spatial detail. This combination of range, precision, and accuracy of spectroscopic measurement in a single instrument is unprecedented. Since its development at JPL in 2012, AVIRIS-NG has investigated a diverse set of Earth environments including deserts, forests, coral reefs, volcanoes, ice sheets and the atmosphere, with deployments in the United States, Mexico, Greenland, and India. In the summer of 2017, it will fly in Canada and Alaska for NASA's Arctic Boreal Vulnerability Experiment (ABoVE) Experiment.

AVIRIS-NG's largest challenge to date was to measure the diverse environments of India in a joint campaign with the Indian Space Research Organization (ISRO) aboard an ISRO research aircraft. The targets selected represented a broad range of spectral composition and brightness, which was difficult to measure with previous spectrometers on a single pass. AVIRIS-NG successfully acquired data from 57 sites across the subcontinent. These included measurements of the Indian Himalayas to investigate properties of snow and ice, including black carbon and dust-induced enhanced melting. Spectra from a wide diversity of ecosystems from dry land to tropical forests were acquired to assess biodiversity and the health of vegetation. Geological and urban targets were also measured to understand the unique spectroscopic signatures of these environments. To round out this mission, data sets of major rivers and coastal environments of India were acquired. Analyses from this campaign have provided new insights leading to exciting concepts for future missions.

Imaging spectrometers like AVIRIS-NG are critical to delivering new and more accurate measurements of the composition and processes of the Earth's rapidly changing environment.

> The combination of range, precision, and spectral accuracy in a single instrument is unprecedented, and early campaigns are providing new insights leading to exciting concepts for future missions.

**A**· Visible and IR radiance and reflectance spectral profile of the of the Pirotan coastal region of India. **B**· AVIRIS-NG successfully surveyed 57 highly varied locations in India, from densely packed urban areas, to snow-covered mountain tops, to coastal shorelines. This range of observational targets demonstrated the instrument's versatility. **C**· A radiance image cube from AVIRIS-NG observations of snow in the Himachal Pradesh region in the Himalayas. The color ranges extending behind the terrain image represent spectrometer readings that can be interpreted to infer information about the ground below, whether it be water, ice, soil, or rock. **D**· Image cube from AVIRIS-NG observations of the Pirotan coastal region of India.

# DRINKING THE WATER ON EUROPA

IN THE PAST TWO DECADES, ROBOTIC SPACECRAFT HAVE MADE REMARKABLE PROGRESS IN THEIR ABILITY TO ANALYZE THE CHEMICAL AND ELEMENTAL MAKEUP OF DISTANT WORLDS. BUT CREATING A MACHINE THAT CAN TEASE OUT THE INDICATORS OF LIFE, YET BE COMPACT AND SUITED TO CHALLENGING ENVIRONMENTS, HAS BEEN A MORE ELUSIVE GOAL. THE SOLUTION MAY COME IN THE FORM OF A LAB-ON-A-CHIP SYSTEM NOW BEING DEVELOPED AT JPL.

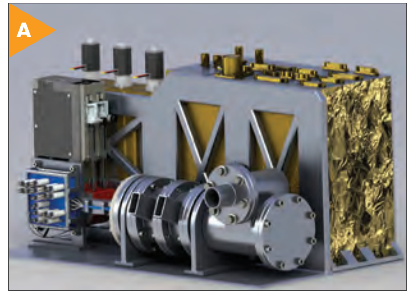
**WE KNOW THAT OUR SOLAR SYSTEM** contains many ocean-bearing worlds. Icy moons such as Europa, Enceladus, and possibly many others appear to have liquid oceans beneath their crust that have occasionally geysered into the frozen surface. The icy residue of this leakage can be analyzed, but searching for biochemical markers at the molecular level requires increasingly sensitive and compact devices. JPL's Microdevices Laboratory (MDL) is developing technology called OCEANS (Organic Capillary Electrophoresis Analysis System) to perform analysis on such samples, prior to delivering them to a mass spectrometer for further examination.

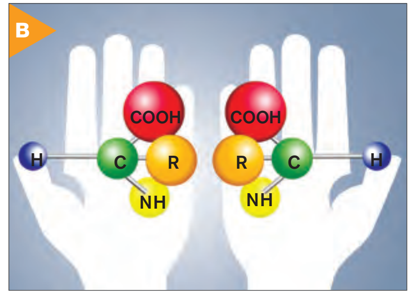
OCEANS is about the size of a laptop computer and will analyze surface samples acquired by scooping or scraping a small amount of ice, which is then melted and injected into a tiny glass tube. As the fluid travels through the tube towards a miniature mass spectrometer, it passes through an electric field. Some molecules travel more slowly in this field than others, depending on their mass. This technique is called capillary electrophoresis (CE). OCEANS uses chemical additives that interact differently with the two different geometric forms of amino acids that will separate these mirror image forms. This measurement of amino acid chirality, or right- versus left-hand twist, may be one of the most powerful chemical indicators of life on other worlds. After this chemical separation is performed, the liquid is delivered from the end of the capillary into a mass spectrometer. Unlike previous approaches, this process allows the liquid sample analyzed by OCEANS to be sprayed directly into the mass spectrometer. This greatly enhances the efficiency and lowers the detection limit for these key target molecules—up to 10,000 times more sensitive than previous devices. The resulting data could provide indicators of living organisms that other systems may fail to detect.

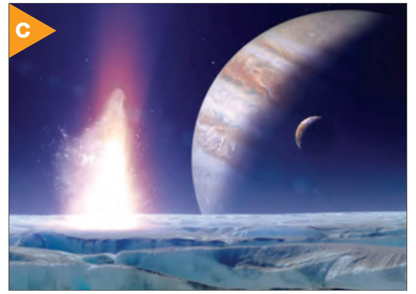
This technology has other advantages over existing sample delivery systems—it is compact and has low energy requirements, allowing the spacecraft to potentially carry additional scientific instrumentation. The analytical parameters are reprogrammable, depending on the sample and desired analysis. Measurements have been demonstrated at a sensitivity of parts per billion. OCEANS may also prove to be useful here on Earth as well, in areas such as environmental monitoring, water analysis, oceanography, and general chemical analysis.

The search for life on other bodies in our solar system is one of the key drivers of space exploration. Technologies such as OCEANS, with minimal power needs and a long lifespan in hostile environments, are considered the analytical heart of future missions to these watery worlds.

OCEANS' measurement of amino acid chirality, or right- versus left-hand twist, may be one of the most powerful chemical indicators of life on other worlds.

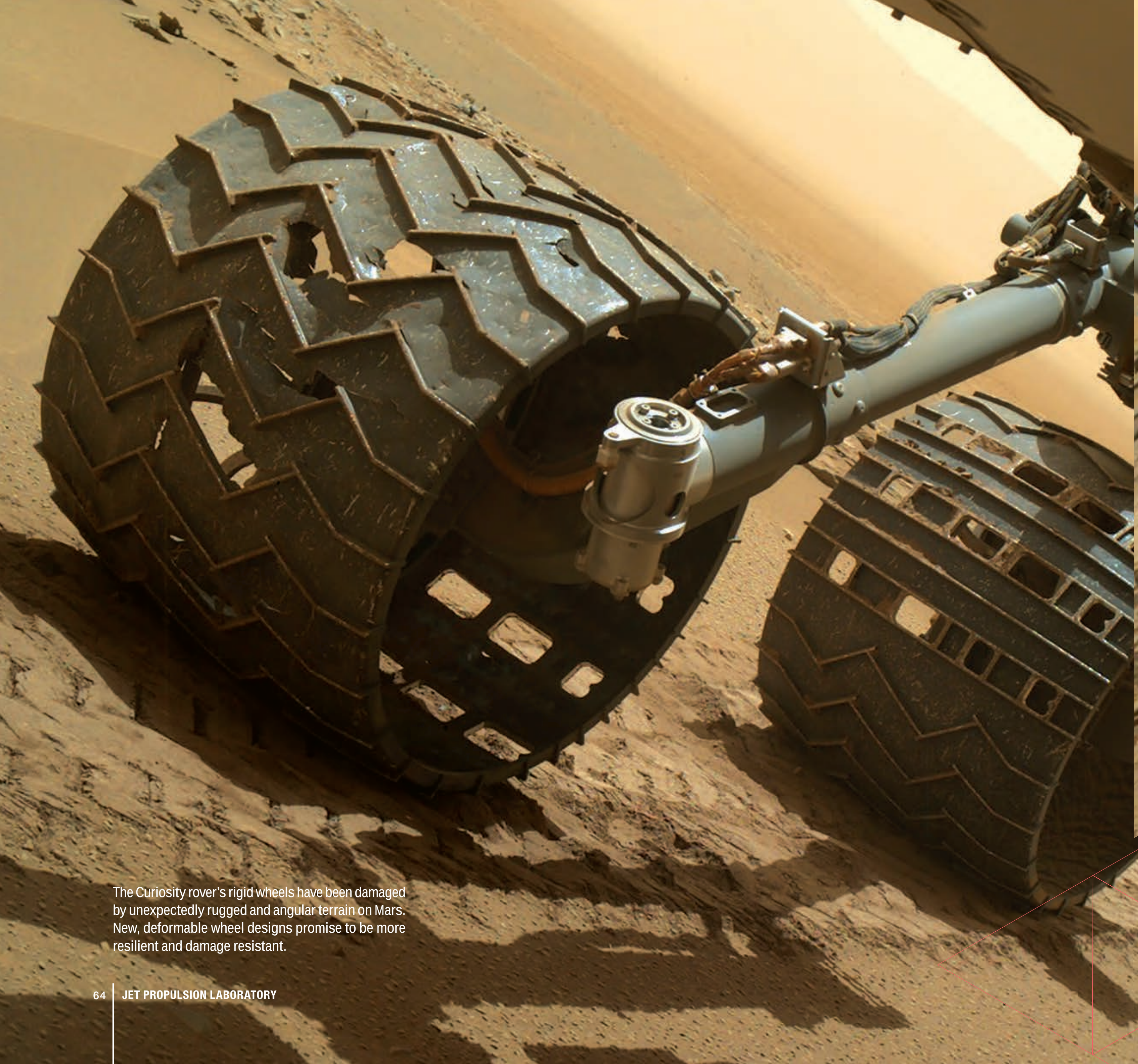






**A·** The OCEANS capillary electrophoresis (CE) valve body is seen at lower left, and the mass spectrometer at lower right. **B·** Chirality is a characteristic of molecules that are mirror images, like your hands. Chirality may be one of the most powerful chemical indicators of life on other worlds. **C·** Jupiter's moon Europa has an ocean of liquid water under its icy surface that may contain life. In this artist's rendering, a geyser sprays some of that water onto the surface. **D·** This artist's rendering illustrates a conceptual design for a potential future mission to land a robotic probe on the surface of Jupiter's moon Europa. The lander could then sample water ice deposited near a geyser. **E·** Successful investigations of OCEANS technology was conducted in the briny water of Mono Lake in California.

A close up the capillary electrophoresis (CE) chip reveals tiny tubes within the chip s structure that **will channel fluid samples for microchip CE and laser induced fluorescence detection.**



The Curiosity rover's rigid wheels have been damaged by unexpectedly rugged and angular terrain on Mars. New, deformable wheel designs promise to be more resilient and damage resistant.

# RED ROUTE ONE

WHEN THE MARS SCIENCE LABORATORY ROVER CURIOSITY LANDED IN 2012, THE FIRST PART OF THE SPACECRAFT TO TOUCH THE RUDDY SURFACE OF THE PLANET WAS ITS SIX ALUMINUM WHEELS. SINCE THEN, CURIOSITY HAS GENERATED AN ENVIABLE LIST OF ACCOMPLISHMENTS, BUT THE WHEELS HAVE PRESENTED ONGOING CONCERNS WITH TRACTION ISSUES, TEARS, AND PUNCTURES IN THEIR THIN ALUMINUM STRUCTURE.

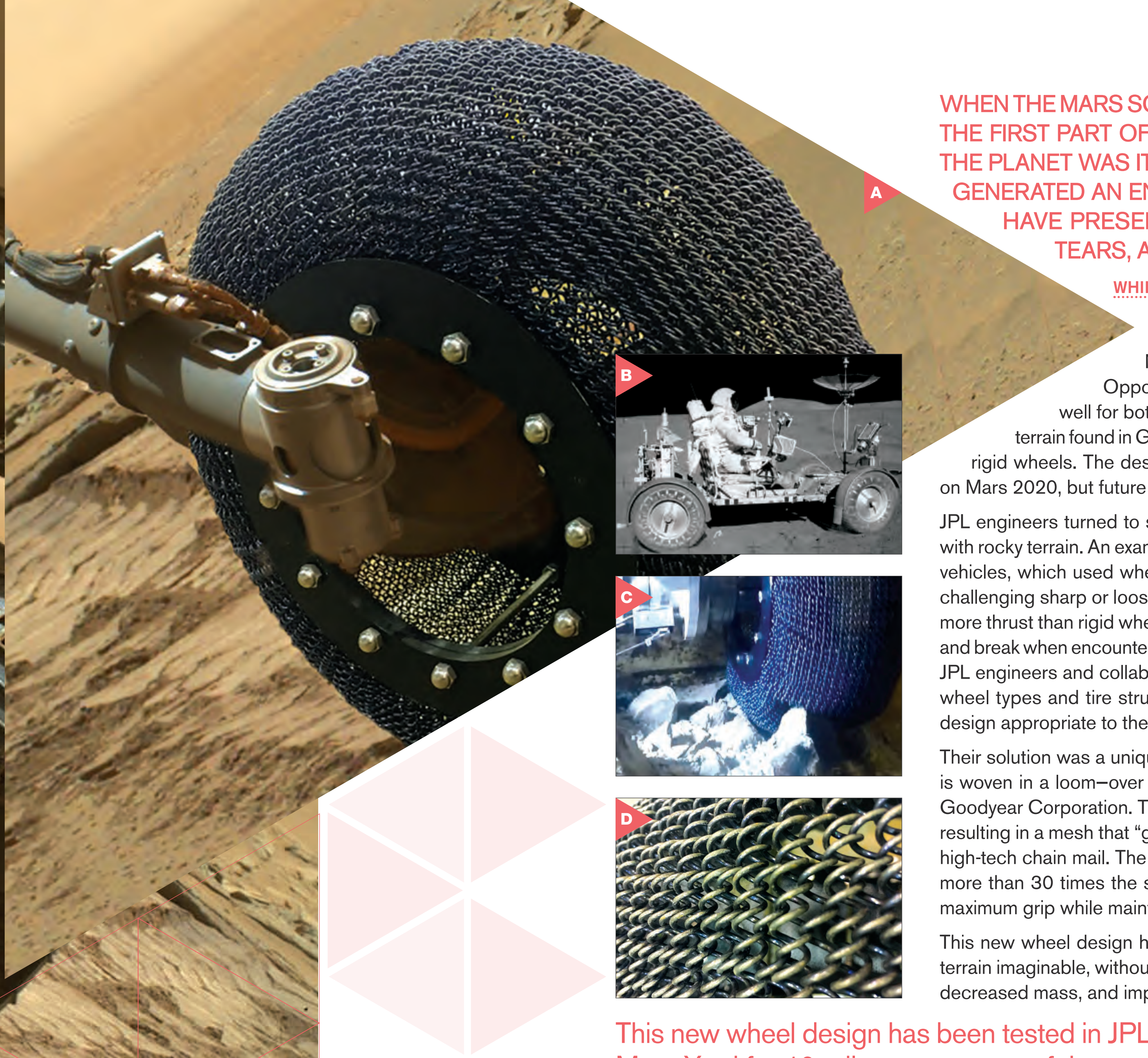
**WHILE THESE INFLEXIBLE WHEELS** were thought to be adequate to the task of supporting the one-ton rover, surface conditions on Mars have proved more varied and challenging than anticipated. Smaller rovers such as the 1997 Mars Pathfinder's Sojourner and the Mars Exploration Rovers Spirit and Opportunity were comparative lightweights, and solid aluminum wheels worked well for both missions. But Curiosity weighs almost 2000 pounds, and the punishing terrain found in Gale Crater has resulted in numerous tears and punctures to its nondeformable rigid wheels. The design of these wheels has been modified (and tested successfully) for use on Mars 2020, but future large rovers to Mars and elsewhere could benefit from new approaches.

JPL engineers turned to softer, deformable wheels for their traction gains and forgiving interaction with rocky terrain. An example of the superior performance of such wheels are the Apollo lunar roving vehicles, which used wheels made from a wire mesh reinforced by metal strips. When these encountered challenging sharp or loose terrain, the wire mesh deformed, creating a flat, long contact patch that provided more thrust than rigid wheels would have. But traditional wire mesh—not unlike a window screen—can spread and break when encountering sharp objects. An improved design for long-duration operation would be needed. JPL engineers and collaborators at NASA's Glenn Research Center (GRC) prototyped and tested multiple wheel types and tire structures. Iterations to improve mass efficiency and durability eventually provided a design appropriate to the demands of Mars rover applications.

Their solution was a unique type of mesh with durable metallic materials. Rather than weaving wire as cloth is woven in a loom—over and under—designers utilized a tire concept developed by NASA's GRC and the Goodyear Corporation. The tire is formed of interwoven alloy spiral springs, much like a springy corkscrew—resulting in a mesh that "gives" without spreading or separating while offering maximum durability—not unlike high-tech chain mail. The springs, composed of a nickel-titanium shape memory alloy, are able to withstand more than 30 times the strain of traditional metals. The result is a wheel that deforms easily, but provides maximum grip while maintaining high durability, even under multiton loads.

This new wheel design has been tested in JPL's Mars Yard for 10 miles, over some of the most punishing terrain imaginable, without damage. Future missions to Mars and other worlds will experience better traction, decreased mass, and improved durability, resulting in longer drives across unexplored landscapes.

This new wheel design has been tested in JPL's Mars Yard for 10 miles, over some of the most punishing terrain imaginable, without damage.



**A-** Wire mesh wheels, made from tough metal alloys, are deformable and have been tested for many miles over rugged, punishing terrain and performed well. **B-** The compliant Mars wheels are improvements on designs developed for the Lunar Roving Vehicle fabricated for the Apollo program in the 1960s. **C-** The Mars compliant wheel has been tested in JPL's Mars simulation testing facilities for over 10 miles with no damage. **D-** The wheel is made of spiral, corkscrew-like nickel-titanium alloy wires that are interwound together to create a tough, resilient mesh.

### 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).

### MARIA ALONSO-DELPINO | PG 12

*Co-Investigator, Spherical Antenna*

Dr. Alonzo-Delpino received her PhD in electrical engineering from the Technical University of Catalonia (Spain) in 2013. At JPL she is a researcher with the Submillimeter-Wave Advanced Technology group in the development of innovative antennas and RF systems at millimeter- and submillimeter-wave frequencies that improve the performance and reduce the mass and power of space instrumentation.

### DARMINDRA ARUMUGAM | PG 25

*Principal Investigator, Precision Outdoor and Indoor Navigation and Tracking*
*for Emergency Responders (POINTER)*

Dr. Arumugam is a Research Technologist in Radar Science and Engineering, and a Program Manager in applied physics in the Civil and Commercial Space Program at JPL. He is the first author of over 50 peer-reviewed technical articles in applied electromagnetics, and leads

### CHARLES MATTHEW BRADFORD | PG 50

*Co-Investigator, Quantum Capacitance Detector*

Dr. Bradford received his PhD in astrophysics and instrumentation from Cornell University in 2001. He develops new instrumentation for long-wavelength astrophysics and studies the evolving interstellar material in galaxies. Current research focuses on new far-IR to millimeter-wave detector systems and wide-band spectroscopic instruments to study the universe's first billion years from mountaintop, balloonborne, and spaceborne platforms.

### 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.

### ROLAND BROCKERS | PG 38

*Principal Investigator, Autonomous Micro Air Vehicle (MAV)*

Dr. Brockers is a Robotics Technologist in JPL's Mobility and Robotic Systems Section. He has more than 17 years of R&D experience in vision-based autonomous navigation of unmanned systems, with a focus on unmanned aerial vehicles since 2010 where he worked on autonomous landing and ingress, visual pose estimation, and autonomous obstacle avoidance for micro air vehicles.

### LANCE CHRISTENSEN | PG 48

*Principal Investigator, Open Path Laser Spectrometer (OPLS)*

Dr. Christensen builds instrumentation for NASA Earth and Planetary Science, and Human Exploration. He is part of JPL's Mars Curiosity Rover Tunable Laser Spectrometer (TLS) team, and leads multi-institutional teams for projects that utilize miniature aerial robotic TLS for applications here on Earth.

### BRIAN DROUIN | PG 36

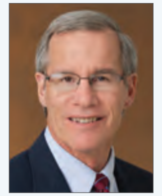
*Principal Investigator, CMOS-Based Spectroscopy Instrument (SpecChip)*

Dr. Drouin holds a PhD in chemistry from the University of Arizona. He is a Research Scientist with the Laboratory and Atmospheric Measurements Group. He has utilized state-of-the-art THz hardware in spectroscopic applications for 15 years. Development of portable THz sensors promises to extend the use of molecular rotational spectra in situ applications.

### PIERRE ECHTERNACH | PG 50

*Principal Investigator, Quantum Capacitance Detector*

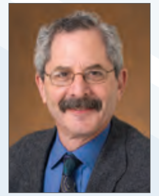
Dr. Echternach received a PhD in physics from the University of Southern California in 1991. He is a member of the Superconducting Devices and Materials group at JPL's Microdevices Laboratory. He uses radio-frequency techniques to study mesoscopic superconducting devices at millikelvin temperatures. Current research concentrates on developing Quantum Capacitance Detectors for applications in astrophysics.



### DAN GOEBEL | PG 44

*Principal Investigator, Ion Propulsion*

Honored for his contributions to low-temperature plasma sources for thin-film manufacturing, plasma materials interactions, and electric propulsion, Dr. Goebel is responsible for the development of high-efficiency electric thrusters, advanced long-life propulsion components, and thruster-life model validation for deep-space missions.



### PAUL GOLDSMITH | PG 12

*Principal Investigator, Spherical Antenna*

Dr. Goldsmith received a PhD in astrophysics from UC Berkeley. He observes interstellar clouds and star formation at radio through submillimeter wavelengths. He is Project Scientist for NASA's GUSTO submillimeter balloon mission, scheduled to fly in 2021. He has designed a wide range of quasioptical systems for astronomy, remote sensing, and communications.

### ROB GREEN | PG 60

*Principal Investigator, Imaging Spectroscopy*

Dr. Green is a science co-investigator on the CRISM imaging spectrometer for Mars, Instrument Scientist for the M3 imaging spectrometer on Chandrayaan-1, 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.

### SARATH GUNAPALA | PG 10

*Principal Investigator, High Operating Temperature Barrier Infrared Detectors*

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

### MITCH INGHAM | PG 26

*Principal Investigator, Resilient Risk-Aware Autonomy*

Dr. Ingham is the Project Software Systems Engineer for the Europa Clipper Mission at JPL. His research interests include model-based methods for systems and software engineering, software architectures, and spacecraft autonomy. He is a core contributor to JPL's Integrated Model-Centric Engineering initiative, and model-based systems and software engineering efforts across the laboratory.

### LAURA JONES-WILSON | PG 20

*Principal Investigator, Magnetic Flux Pinning for Orbiting Sample Capture*

Dr. Jones-Wilson earned her PhD in dynamics and control space systems at Cornell University in 2012. She is a guidance and control systems engineer at JPL where she serves as the Principal Investigator for a technology development project exploring the use of magnetic flux pinning for potential orbital sample capture missions.

### JAAKKO KARRAS | PG 32

*Principal Investigator, Pop-Up Flat Folding Explorer Robots (PUFFER)*

Jaakko Karras received an MS in electrical engineering from the University of California, Berkeley, where he performed research on bio-mimetic origami robots. He is now leading the JPL PUFFER team to develop origami-inspired rovers for use with future NASA missions.

# CONTRIBUTORS PROFILES

### TOM KUIPER | PG 18

*Principal Investigator, Deep Space Network Transient Observatory*

Dr. Kuiper received a PhD in astronomy from the University of Maryland. He joined JPL to conduct radio studies of the interstellar medium using the largest antennas of NASA's Deep Space Network. As Lead Radio Astronomer for the DSN, he oversees the development of hardware and software for astronomy research.

### ERIC KULCZYCKI | PG 58

*Principal Investigator, Mars Sample Transfer Test-bed*

Eric Kulczycki received his MS degree in mechanical and aeronautical engineering from the University of California, Davis, in 2006. He is the Principal Investigator for Mars Sample Transfer Test-bed Research and Technology Development Task and is currently working on the Mars 2020 Rover mission.

### SCOTT MORELAND | PG 64

*Co- Investigator, Mars Compliant Wheel Development*

Dr. Moreland is a member of the Robotic Vehicles and Manipulators Group at JPL. His work typically involves systems that interact with the ground either for mobility or sampling purposes. Of particular interest to Dr. Moreland is the development of traction devices for extreme surface materials and micro-gravity environments.

### PANTAZIS MOUROULIS | PG 22

*Co-Investigator, Snow and Water Imaging Spectrometer (SWIS)*

Dr. Mouroulis is a Senior Research Scientist, Principal Engineer, and Supervisor of the Optical Technology Group at JPL, where he works on imaging spectroscopy and instrumentation. He is a Fellow of SPIE and OSA, and a recipient of the NASA Exceptional Technology Achievement Medal for spectrometer development.

### RUDRA MUKHERJEE | PG 54

*Principal Investigator,*
*Laboratory Demonstration of Autonomous Robotic Assembly*

Dr. Mukherjee is a Research Technologist and Group Leader in the Robotics Modeling and Simulation group at the Robotics and Mobility Systems section at JPL. He has been a NASA SBIR topic manager as well as JPL representative for NASA's Strategic Capability Leadership Team on Rendezvous and Capture.

### SHOULEH NIKZAD | PG 28

*Principal Investigator, Advanced Detectors, Systems, and Nanoscience*

Dr. Nikzad holds a PhD in applied physics from Caltech. She is a Senior Research Scientist, Principal Engineer, and the lead for the Advanced Detectors, Systems, and Nanoscience Group. Her research focus is in developing high-performance silicon and gallium nitride–based detectors, UV imaging spectrometers, and cameras.

### AARON PARNESS | PG 46

*Principal Investigator, Microspine Gripper and Anchoring Drill*

Dr. Parness performs research on the attachment interfaces between robotic systems and their surrounding environment, working primarily on climbing robots and robotic grippers. An expert in novel methods of prototype manufacturing, he has experience in microfabrication, polymer prototyping, and traditional machining (both manual and CNC).

### DRAGANA PERKOVIC-MARTIN | PG 16

*Principal Investigator, DopplerScatt*

Dr. Perkovic-Martin received her PhD from the University of Massachusetts, Amherst, in 2008. She is currently a group supervisor of the Radar System and Instrument Engineering group in the Radar Science and Engineering Section, and is the lead radar system engineer for Mars 2020 and the PI for the DopplerScatt Instrument Incubator Program and Airborne Instrument Technology Transition program.

### JAGDISH PATEL | PG 8

*Principal Investigator, Solid-State Neutron Detectors (SSND)*

Dr. Patel received a PhD from the University of Illinois at Urbana-Champaign in 1992. He is working on a solid-state neutron detector (SSND) using ultra-thin high resistivity silicon detectors that offers critical functionality in neutron energy spectroscopy and directionality for nuclear threat detection.

### RAUL POLIT-CASILLAS | PG 14

*Principal Investigator, 4-D Printed Integrated Architectures*

Raul Polit-Casillas is a graduate from ISU (MSc, France) in 2011 and UPV (MS Arch, Spain) in 2008. He is an active member of AIAA with regular publications while he is working on his PhD research. With several awards from JPL and NASA for his innovative work, Raul works with a team of experts at JPL to design and build complex space systems.

### MARC POMERANTZ | PG 34

*Task Manager, Ranger: Browser-based Visualization for Education, Public Outreach and Engineering*

As a Robotics Technologist in the Mobility and Robotic Systems section at JPL, Marc Pomerantz leads teams that design, develop and deploy innovative, real-time 3-D visualization and robotic vehicle simulation software systems in support of JPL flight, research, and public outreach projects.

### STAN SANDER | PG 30

*Principal Investigator, Panchromatic Fourier Transform Spectrometer Engineering Model*

Dr. Sander is a Senior Research Scientist in JPL's Earth Science Section. His work focuses on laboratory photochemistry and kinetics of Earth and planetary atmospheres, measurements of atmospheric trace gases and greenhouse gases, and development of new instruments for studying atmospheric composition from space.

### EUGENE SERABYN | PG 52

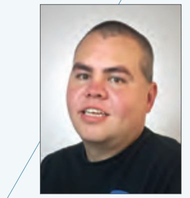
*Co-Investigator, Dual-Stage Vortex Coronagraph*

Dr. Serabyn received his PhD in physics from UC Berkeley in 1984. He is a Senior Research Scientist working on developing high-contrast techniques for exoplanet detection and characterization, as well as novel microscopy techniques for in situ life detection.

### MARSHALL SMART | PG 24

*Principal Investigator, Li-Ion Cells Battery Electrochemical Technologies*

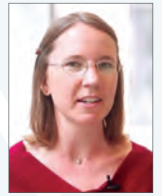
Dr. Smart received a PhD in chemistry from the University of Southern California in 1998. He is currently a Principal Member of the Technical Staff in the Electrochemical Technologies Group, as well as the Cog-E of Energy Storage (Li-ion) for the Europa Clipper project.



### ADRIAN TANG | PG 40

*Principal Investigator, Advanced CMOS technologies/Snow Radar Instrument*

Dr. Tang received his PhD from UCLA in electrical engineering and is leading work at JPL focused on infusing CMOS system-on-a-chip technology from the gaming and mobile phone markets into spaceflight instruments. He is an active contributor to many IEEE publications in the areas of solid-state and radio frequency integrated circuits.



### KIRI WAGSTAFF | PG 56

*Principal Investigator, Machine Learning and Instrument Autonomy (V-FASTR)*

Dr. Wagstaff received her PhD in computer science from Cornell University in 2002. She researches and develops new machine learning systems for real-world problems from areas such as astronomy and planetary science. She also serves as a Tactical Uplink Lead for the MER Opportunity rover.

### PETER WILLIS | PG 62

*Principal Investigator, Organic Capillary Electrophoresis Analysis System*

Dr. Willis received a PhD in chemistry from Cornell University in 1999. He is developing liquid-based chemical analyzers that can be used in the search for life on robotic missions to ocean worlds such as Europa and Enceladus.

### FENG ZHAO | PG 6

*Deputy Project Manager, WFIRST*

Dr. Zhao received his PhD in electrical engineering from Pennsylvania State University. He led picometer metrology technology development for SIM, and advanced metrology for AMD. He has been leading high-contrast imaging technology development since 2013. He is currently deputy project manager of the WFIRST Coronagraph Instrument Project.

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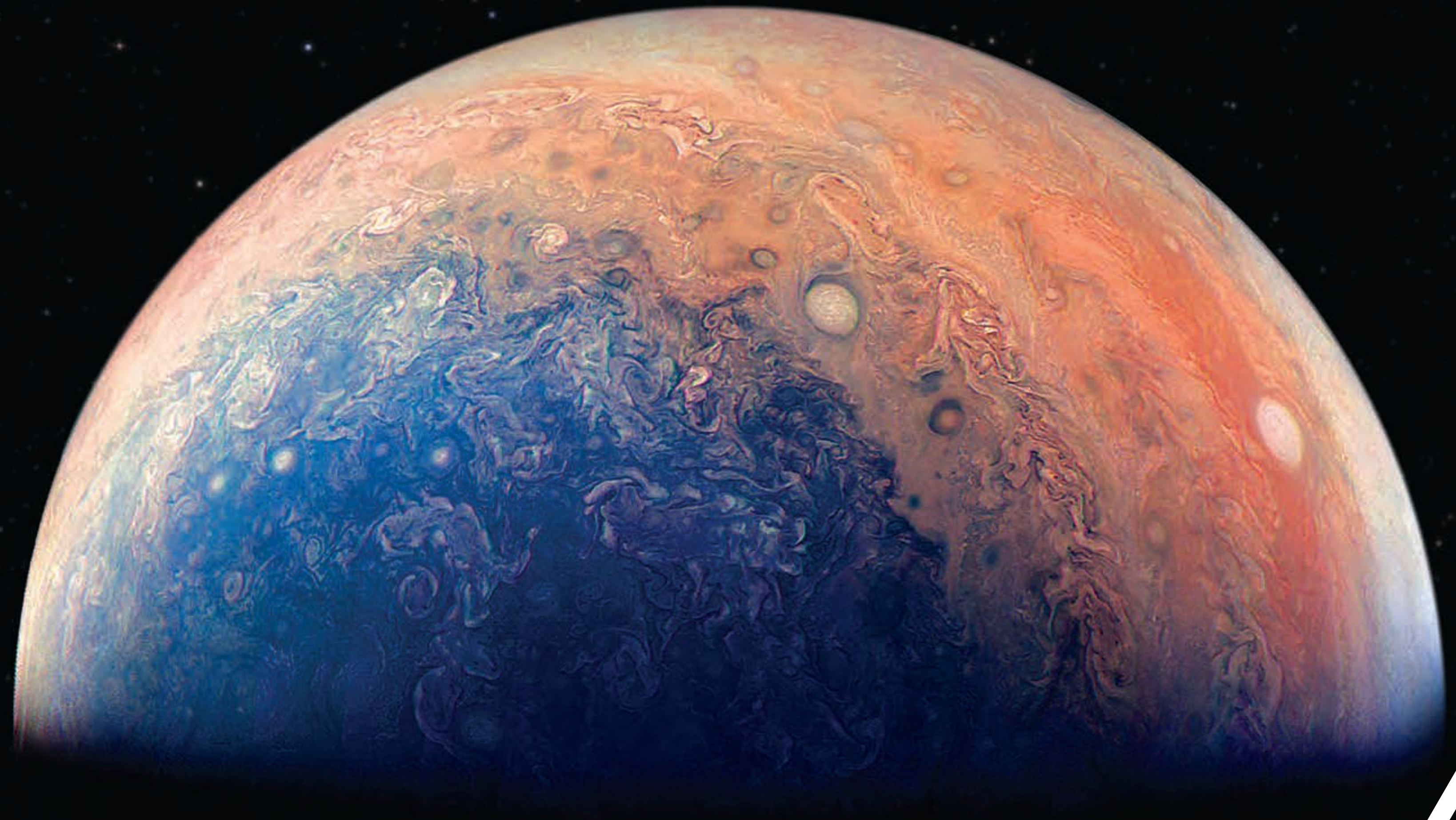
JPL, a world leader in planetary exploration, Earth science, and space-based astronomy, leverages investments in innovative technology development that support the next generation of NASA missions, solving technical and scientific problems of national significance.



**The oval features that dot the cloudscape in this enhanced color image of Jupiter's south pole, as seen by NASA's Juno spacecraft from an altitude of 32,000 miles (52,000 kilometers), are cyclones up to 600 miles (1,000 kilometers) in diameter. Multiple images taken with the JunoCam instrument on three separate orbits were combined to show all areas in daylight, enhanced color, and stereographic projection. Credit: NASA/JPL-Caltech/SwRI/MSSS/Gabriel Fiset**

The JPL 2016–2017 Technology Highlights document 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 2016 and 2017, many other technologies remain equally important to JPL's ability to successfully contribute to NASA's space exploration missions, including mature technologies that are commercially available and technologies whose leadership is firmly established elsewhere.

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