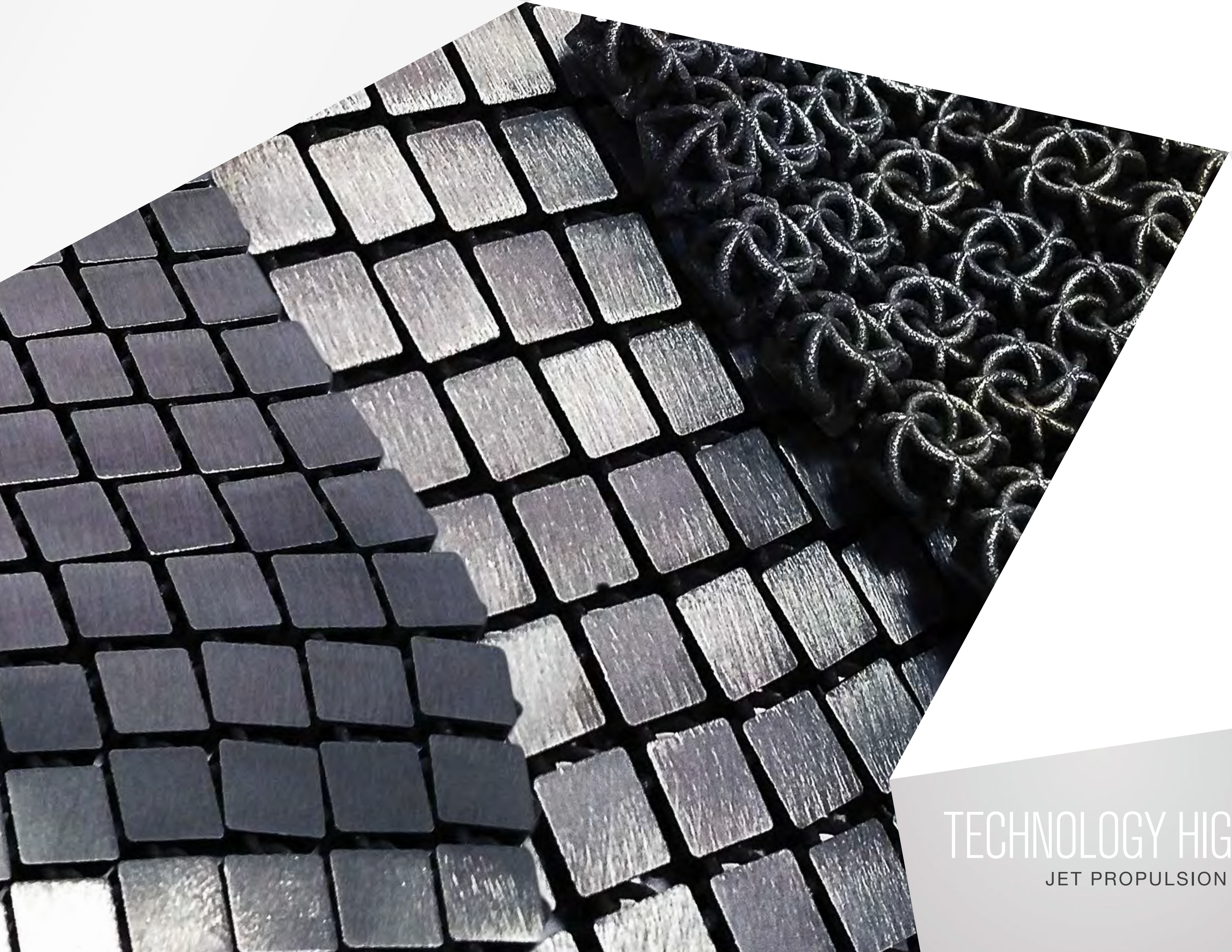
National Aeronautics and Space Administration



2015-2016

TECHNOLOGY HIGHLIGHTS

JET PROPULSION LABORATORY

The work, the goals, the achievements at JPL are based in exactitude, objectivity, and methodological rigor. They are powered in many ways, though, by the dreams and aspirations of the kind of individuals who could imagine rockets back when the rest of the world was being dazzled by the new idea of airplanes. Their dreams are reflected in the technologies described in these pages.

ABOUT THE COVER: JPL researchers pioneered the use of advanced design techniques to create novel geometries such as the 3D-printed woven textiles shown on the cover. By combining geometries, and with innovative research into material properties, researchers at JPL are able to "print" functions into the fabrics using additive manufacturing. Other novel geometric design techniques use folding structures inspired by origami. JPL collaborated with origami master and former JPL employee Robert Lang to design and implement deployable structures that incorporate origami; projects include the Large Deployable Solar Array and the flower-shaped starshade. The unique patterns and underlying complexity of origami also informed the art and design of this publication. Visit us at **www.jpl.nasa.gov**.

2015-2016 TECHNOLOGY HIGHLIGHTS

JPL is a place where talented people come to work to get things done. 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 numerous creations orbit Earth and other planets, rove on the surface of Mars, or use powerful telescopes to peer into the distant universe.

Over the decades, we have learned to do these things in a very disciplined fashion in order to avoid mistakes and to meet demanding schedules and budgets. We expect our teams to learn and embrace this discipline, borne of many hard lessons.

But we also encourage our people to dream. These are not idle dreams – being JPLers, they dream about the future and its enormous possibilities, and their dreams are reflected in the technologies described in these pages. Some dream about flying to an asteroid using powerful ion engines and then picking up a sample using bio-inspired microspine grippers. Others imagine deploying a robot that explores an asteroid or comet by hopping on its surface. Serious roboticists talk about machines that crawl upside down underneath a thick layer of ice that encapsulates the mysterious ocean worlds on the moons of the giant planets in the outer solar system.

Communication experts plan to carefully target a laser toward Earth from deep space to beam down huge volumes of images and scientific data gathered by the host spacecraft or its companions. Highly analytical computer scientists aim to endow these spacecraft with enough intelligence to allow them to make decisions autonomously, without waiting to receive human-generated instructions from Earth that could take hours to arrive while traveling at the speed of light. Gifted mechanical engineers embrace the severe challenge of building large structures known as starshades to perform a delicate, complex dance as they unfold in space, while afterwards achieving the incredible precision needed to block out the light from a distant star at the part-per-billion level needed to let a space telescope examine the planets orbiting around it.

The magic of JPL is in bringing dreamers and doers together to accomplish things that have never been done before, and which often seem scarcely imaginable. This has been true since the very beginning: many decades ago, our founders called what they worked on jet propulsion because rocketry was obviously crazy. They dreamed of using rockets to orbit Earth and travel to the Moon, but they also developed the discipline to find solutions to the hard, practical problems of making rockets reliable and useful, leading America into the space age in the process. JPLers then took aim at exploring the planets, and subsequently demonstrated the ingenuity and discipline needed to solve the numerous, difficult technical challenges to actually do it. As you review the technologies represented in this book, it's worth remembering JPL's legacy of both dreaming and doing.

The creativity and bold vision on display here have made me exceedingly proud to serve as JPL's Director for the past decade and a half. I know that as JPL transitions to its next leader, even more amazing missions and technology developments are yet to come.

Charles Elachi
JPL Director

Extraordinary achievements require considerable forward-thinking investment in research and technology development. For example, after decades of support by the National Science Foundation and Caltech, the Laser Interferometer Gravitational-Wave Observatory (LIGO) yielded one of the greatest discoveries of the 21st century – the detection of gravitational waves. We dedicate this publication to the vision and leadership that makes these remarkable achievements possible.

The image above represents a computer simulation of two black holes prior to merging. The dual LIGO detectors identified this cataclysmic event, 1.3 billion light-years away, as a transient gravitational-wave signal matching the waveform predicted by Einstein's theory of general relativity. After more than 50 years of experimental and theoretical efforts, it was the first direct detection of gravitational waves and the first observation of a binary black hole merger. The graph illustrates gravitational-wave signals detected by the two LIGO observatory locations at Livingston, Louisiana, and at Hanford, Washington, on September 15, 2015.

JPL OFFICE OF CHIEF TECHNOLOGIST

If you mention the word technology, today most people would think of the internet, social media, or their smartphone. Indeed, when I open my email inbox, on most days I can find messages from salespeople who were hoping to reach JPL's CIO instead of its Chief Technologist.

The broader meaning of the word is reflected in these pages: it boils down to the collection of knowledge and artifacts that we use to solve practical problems – for instance, how to land a 1-ton rover on Mars. But seriously, that's the point: at JPL, we tackle some really hard but very interesting problems that have not been solved before, and finding the solutions requires a lot of technological ingenuity.

Fortunately, we live in a time of technological abundance: We are blessed with technologies that are far more powerful than were available to the JPLers who pioneered planetary exploration decades ago. Today a computer the size of a credit card is orders of magnitude faster than the room-filling mainframes of the 1970s, allowing us to put algorithms onboard a spacecraft that previously were far too complex to consider. Sensors of all kinds – especially image sensors – are dramatically smaller, much higher performing, and far more versatile. We have semiconductor lasers, radio-frequency integrated circuits, and field-programmable gate arrays that would have seemed like magic just a few decades ago. Our tools are also far better. Whether we are using model-based systems engineering, computer-aided design, electronic design automation, or physical modeling, we are able to generate better designs much more quickly. Our ability to instantiate these designs has also improved dramatically, whether we are using numerically-controlled machine tools, 3D printing, or deep-ultraviolet projection lithography.

In short, and as these pages reflect, the technological opportunities at JPL have never been greater. Our primary challenge is to seize these opportunities and to reduce these ideas to practice, while finding ways to manage the attendant complexity and risk. We must embrace this bright future – just as JPL always has.

Jonas Zmuidzinas
Chief Technologist

Fred Hadaegh
Associate Chief Technologist

Rio de Janeiro and Sao Paulo at night as the International Space Station orbits Earth.

CONTENTS

JPL QUESTS

With a host of planetary science, Earth science, astrophysics, and technology demonstration missions planned for the coming decade, JPL has an opportunity to pursue some of NASA's most challenging scientific and technical quests. The quests listed here provide a blueprint for designing our missions going forward and the benchmark for measuring our successes.

Hubble Space Telescope image of the spiral galaxy Messier 83.

1 HAS THERE EVER BEEN LIFE ELSEWHERE IN OUR SOLAR SYSTEM? COULD IT BE THERE TODAY?

COULD LIFE HAVE EVER FOUND A FOOTHOLD ON ANOTHER PLANET SUCH AS MARS, OR ON THE MOONS OF THE GIANT GASEOUS OUTER PLANETS? JPL is studying high-priority future missions to characterize Jupiter's moon Europa to assess its potentially life-friendly environment, or to return samples from Mars to assess whether that planet is habitable or could have ever hosted life.

2 ARE THERE PLANETS LIKE EARTH ELSEWHERE IN THE UNIVERSE?

ARE WE ALONE? ARE THERE OTHER PLANETS LIKE OURS? DOES LIFE EXIST ELSEWHERE IN THE UNIVERSE? Every new discovery of a planet beyond our solar system helps us refine our notion of the cosmos and understand humankind's place within it. JPL is at the forefront of efforts to discover Earth-like planets, enabled by our work in developing the technologies and next-generation telescopes needed to detect and characterize habitable planets, measure their atmospheres, and find the chemical signposts of life.

3 HOW DID THE UNIVERSE BEGIN, AND HOW IS IT EVOLVING?

WHAT COULD BE A BIGGER QUEST THAN SETTING OUT TO UNDERSTAND THE ORIGIN, NATURE, AND EVOLUTION OF THE UNIVERSE? HOW DID IT BEGIN? HOW DOES IT WORK? AND ULTIMATELY, HOW WILL IT END? To help answer these questions, JPL's reach has extended from Earth to the Sun to the Big Bang, as we investigate how galaxies and stars form and evolve, the nature of the interstellar medium, and the cosmic microwave background left from the universe's earliest epoch. JPL is poised to continue to help unravel such mysteries as interstellar clouds, magnetic fields in the Milky Way's dense clouds, dark matter and dark energy, and gravitational waves caused by rapidly accelerating matter such as supermassive black holes.

4 HOW DID OUR SOLAR SYSTEM FORM AND EVOLVE?

FROM THE OUTSET, JPL HAS BEEN THE GLOBAL LEADER IN EXPLORATION OF THE SOLAR SYSTEM, AND WE WILL CONTINUE THE QUEST TO DEEPEN OUR UNDERSTANDING OF OUR COSMIC NEIGHBORHOOD. Future missions will target the primitive celestial bodies that contain the building blocks of the solar system, the giant planets and their moons whose formation and evolution disclose essential planetary processes, to potentially dangerous Earth-crossing objects such as comets and asteroids.

5 WHAT CHANGES ARE HAPPENING TO OUR OWN PLANET?

OF ALL THE WORLDS STUDIED BY JPL, THE QUEST TO UNDERSTAND HOW EARTH IS CHANGING TOUCHES US MOST DIRECTLY. Although we have made major advances in understanding our home planet, it often seems as if we are still just scratching the surface. How high will the seas rise? How available will water be in the future? How are carbon storage and biodiversity changing? How can we better prepare for extreme events like earthquakes and volcano eruptions? Such questions will continue to drive JPL to innovate new ways to observe how Earth responds to both natural and human-induced changes, and to provide actionable results for research, education, and decision-making.

6 HOW CAN JPL HELP PAVE THE WAY FOR HUMAN EXPLORATION OF SPACE?

AT THE DAWN OF THE SPACE AGE, JPL PREPARED THE WAY FOR THE APOLLO ASTRONAUTS TO REACH THE MOON BY SENDING FORERUNNER ROBOTIC MISSIONS, AND IN RECENT YEARS, WE HAVE TAKEN ON A SIMILAR ROLE IN NASA'S JOURNEY TO MARS. As NASA charts plans to send humans to the Red Planet, JPL's trove of scientific and engineering experience will prove indispensable. In addition to robotic rovers and orbiters, JPL is developing new technologies to support future human exploration, including such initiatives as the Low-Density Supersonic Decelerator and a possible Mars Helicopter. To demonstrate and prove new capabilities needed for future human missions, JPL is leading the proposed Asteroid Redirect Robotic Mission. This mission may also help NASA understand how to use asteroids as resources when humans embark on explorations beyond our Moon.

7 CAN WE USE JPL'S UNIQUE EXPERTISE TO SERVE OUR NATION AND ITS PEOPLE?

JPL'S QUEST FOR EXCELLENCE DRIVES A WIDE ARRAY OF TECHNOLOGICAL ADVANCES, YIELDING PRACTICAL APPLICATIONS THAT TOUCH SOCIETY FAR BEYOND THE SPACE PROGRAM. We have a long tradition of providing specialized help in the civil, commercial, and security sectors, working closely with partners outside NASA to tackle issues of national priority.

Jakob van Zyl
Laboratory Associate Director

MADE IN THE SHADE **FINDING LIFE** IN THE SHADE OF A STAR

Up to half the size of a football field, a starshade would journey into space as a companion to a telescope, deploy and unfurl its "petals", and fly in formation up to 50,000 kilometers away from the telescope to take position in front of a star of interest. The unique shape of the flower-like starshade creates a near-perfect shadow of the star, allowing the telescope to reveal the planets orbiting in its habitable zone – the Goldilocks "not too hot and not too cold" distance from the star.

The universe is teeming with planets. Astronomers now believe that every star in the galaxy has a planet, and they speculate that up to one fifth of them have an Earth-like planet in the right orbit that might be able to harbor life, but we haven't seen any of them.

We've only detected them indirectly because they are too dim and too close to their parent stars – all we're currently seeing is the big beaming image of the star that's ten billion times brighter than the planet. The light from the star creates a very bright image inside the telescope that washes out the tiny planet.

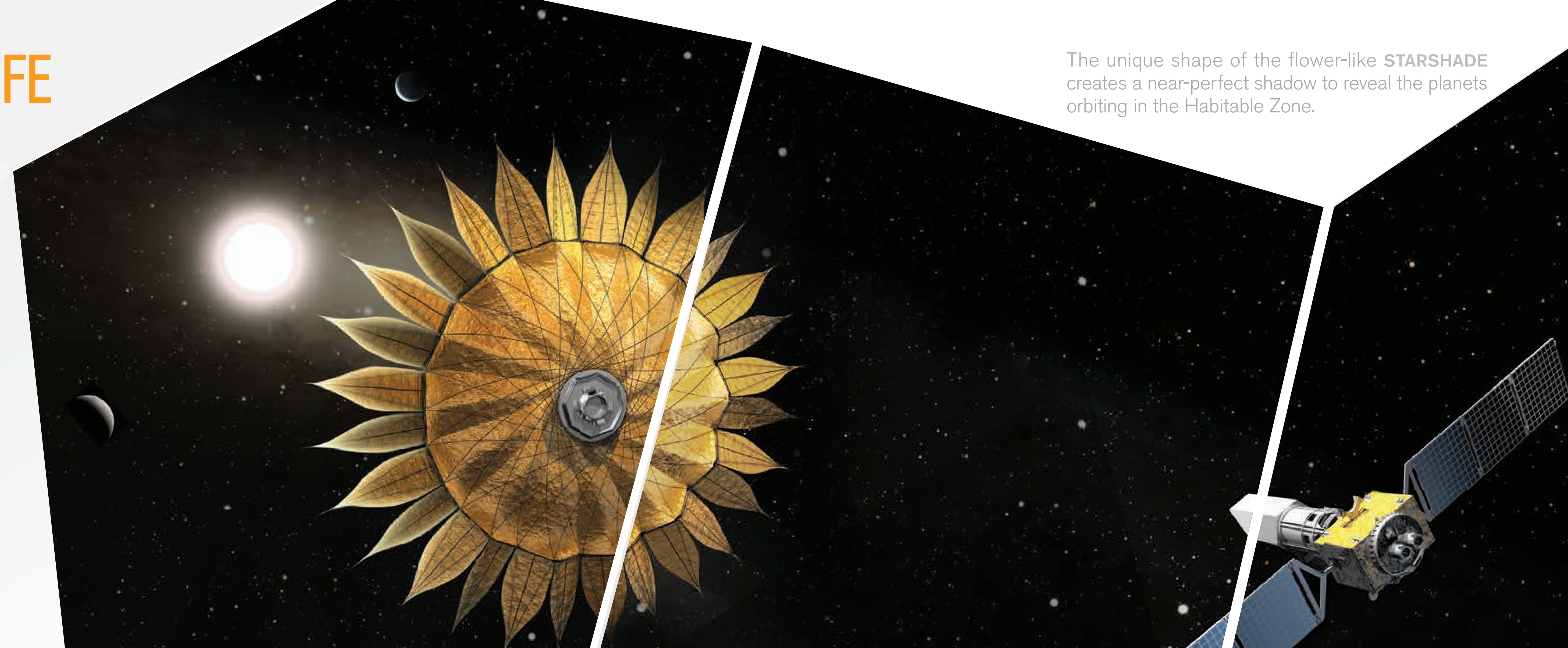
It's kind of like being on stage and putting your hand in front of the spotlight shining in your eyes to see someone in the back row. But imagine you are in Los Angeles trying to see a baseball that's close to a large searchlight pointing right at you… from San Francisco. It's the same to see the planet; not only do we need to see something very tiny, we have to get rid of all that star light.

In summer 2015, the team tested a half-scale model of a 34m diameter deployable starshade structure at JPL.

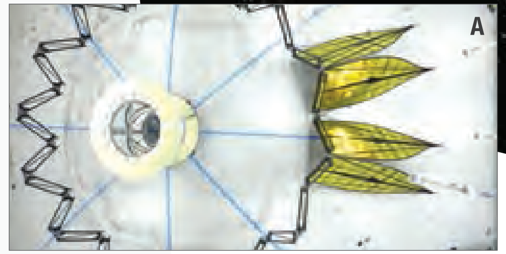
To be successful, 7m long petals need to unfurl with a shape that is precise to within a few human hair widths. The structure must then rotate, deploy and position the petals around a 20m diameter central disc structure to within a fraction of a millimeter.

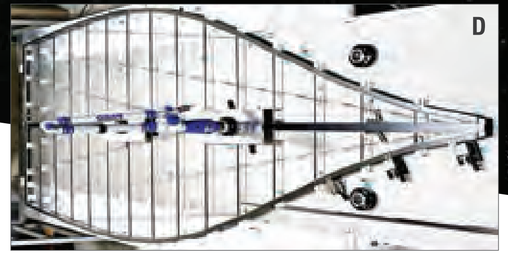
The petal shapes and positions must then stay that way for years in the harsh space environment. The team showed with 20 deployments that the structure places the petals to within about a tenth of a millimeter of the correct spot every time.

These successful tests take us another step closer to getting a picture, a star's family portrait of planets made in the shade, where we may just see another pale blue dot that could harbor life.



The unique shape of the flower-like **STARSHADE** creates a near-perfect shadow to reveal the planets orbiting in the Habitable Zone.



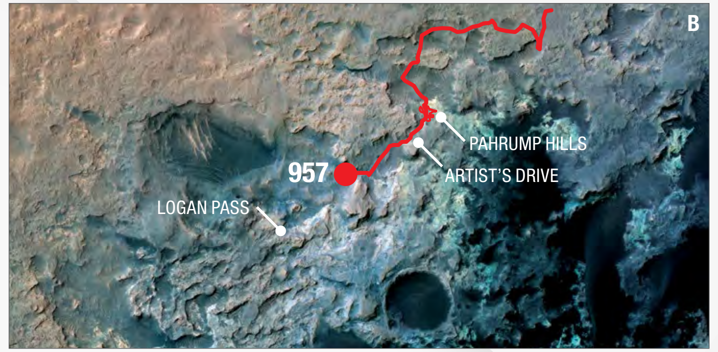


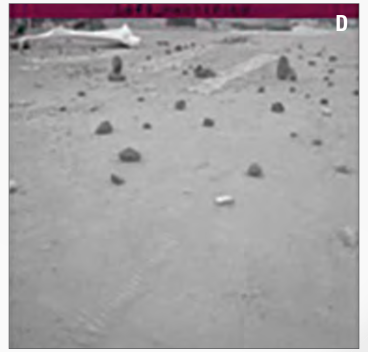
[A] Bird's eye view of half-scale starshade prototype mid-deployment at JPL, summer 2014. **[B]** Early prototype of stowed starshade with flower-like petals ready for unfurling, fall 2013. **[C]** Starshade half-scale prototype fully deployed with 4 of 28 petals in the JPL Advanced Large Precision Structures Lab, 2015. **[D]** Early prototype full-scale 6-m starshade petal, 2010.

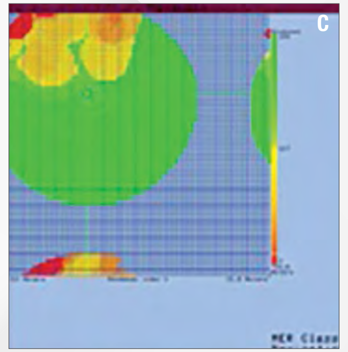
Artist concept of starshade almost fully deployed moving into position between the target star and the telescope

Mars Science Laboratory's Vehicle System Testbed (VSTB) in JPL's MarsYard test facility.

ROVE MARS FASTER, FURTHER, SAFER







[A] Tracks left by the Opportunity rover on Mars while autonomously avoiding a group of rock hazards on Sol 1160 (April 29, 2007). **[B]** A red dot marks the location of the Curiosity rover on the day that brought the mission's total driving distance past the 10-kilometer mark (6.214 miles). **[C-D]** JPL's MarsYard test facility images taken by the MSL's Vehicle System Testbed (VSTB) and the resulting terrain "goodness" map generated by the Rover's autonomous navigation software, Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT).

Mars rover FastTraverse enables much faster autonomous rover navigation, increasing the time available for driving. Planetary rovers have traditionally been limited by the available computational power in space qualified processors.

When driving autonomously, limited computation means that the Mars Science Laboratory (MSL) rover must stop for a substantial period while the navigation software identifies a hazard-free path using acquired imagery. The resulting limitation on driving duty cycle reduces the rover's average traverse rate.

FastTraverse enables planetary rovers to drive faster, farther, and more safely by transitioning computation-intensive portions of autonomous navigation processing from the main CPU to a field-programmable gate array (FPGA) coprocessor. What currently takes many seconds or even minutes on state-of-the art radiation hard processors can be accomplished in milliseconds using FPGA implementations.

In 2015, FastTraverse was integrated with and demonstrated on MSL's Vehicle System Testbed performing autonomous navigation in JPL's outdoor MarsYard facility. The FPGA–enhanced capabilities demonstrated were: hazard detection/avoidance and Visual Odometry.

FastTraverse technology establishes a pathway for rover traverse rates of 60-80 m/hr for future MSL-class rovers compared to current rates of 15-35 m/hr, while increasing safety by enabling always-on visual odometry and hazard detection. The FastTraverse project leveraged a long series of development efforts funded by the Defense Advanced Research Projects Agency (DARPA), U.S. Army, Navy, and the Space and Naval Warfare Systems Command (SPAWAR).

What currently takes many seconds or even minutes on state-of-the art radiation hard processors can be accomplished in milliseconds using FPGA implementations.

LOOK, MOVE, AND STICK THE LANDING

Engineers at JPL have been developing cutting-edge technologies that would enable spacecraft to “stick a landing” on Mars — or any other planetary body — with more precision than ever before.

In 2015, JPL completed a multi-year effort to develop and demonstrate Terrain Relative Navigation (TRN) at Mars. Prior Mars landers have landed effectively “blind”, with no information on their specific touchdown point relative to local hazards. This leaves the lander vulnerable to landing site hazards and forces the selection of “safe” landing sites that in many cases preclude selection of the most scientifically compelling sites.

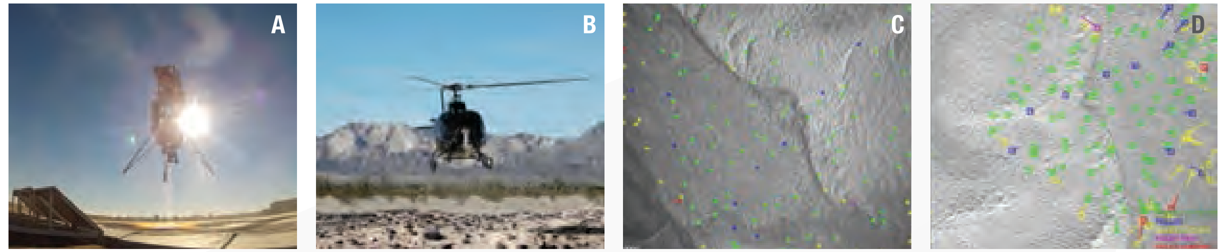
TRN addresses this by using a Lander Vision System (LVS) on the descent vehicle to acquire images of the landing site while descending. These pictures are then compared to an image of the terrain stored onboard, allowing the vehicle to autonomously find its position relative to the landing site. With this knowledge, the lander can execute a divert maneuver to avoid any identified hazards and target a safe touchdown point. During this multi-year effort, the LVS was tested in multiple field campaigns, including helicopter testing in the California desert, as well as in the Autonomous Descent and Ascent Powered-flight Testbed (ADAPT), a JPL test campaign conducted in Mojave, CA utilizing Masten Space System’s Xombie vertical take-off/landing rocket. These tests were designed to validate LVS over a wide operational envelope defined by expected Mars 2020 conditions.

Based on the success of these field tests and subsequent data analysis to refine the LVS algorithms, this technology has now been baselined for use in the Mars 2020 mission. Inclusion of TRN will enable consideration of a much richer set of potential landing sites.

This technology represents a huge step forward in future capabilities for safe and precise Mars landing, and demonstrates a highly effective approach for rapid, low-cost validation of new technologies for the entry, descent and landing of spacecraft. This same technology has valuable applications to landing on the Moon, asteroids and other space destinations of interest.

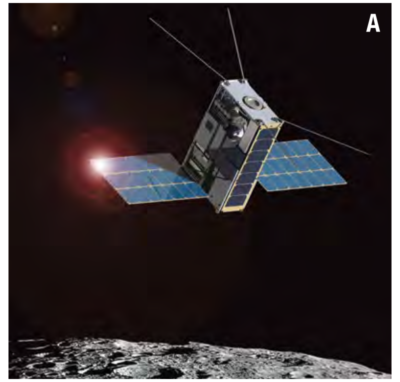
The TRN demonstration was developed in partnership with Masten Space Systems.

Prior Mars landers have landed effectively “blind”... **TRN** addresses this by using a Lander Vision System (LVS) on the descent vehicle to acquire images of the landing site while descending.

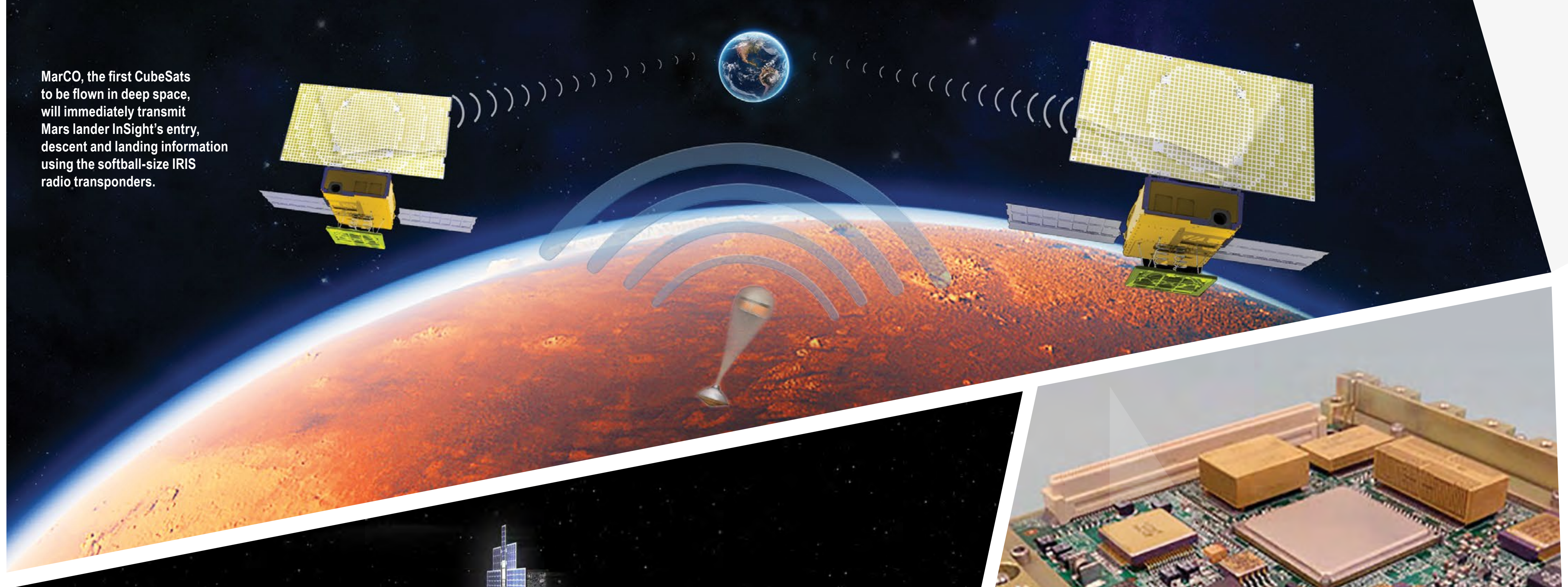


[A] Testing of the LVS payload on the Autonomous Descent and Ascent Powered-flight Testbed, in-flight at Mojave, CA. **[B]** LVS helicopter field testing over Mars-analog terrains. **[C-D]** LVS correlates camera images collected in flight (left) against a pre-stored map (right) to accurately determine the vehicle position, attitude, and velocity.

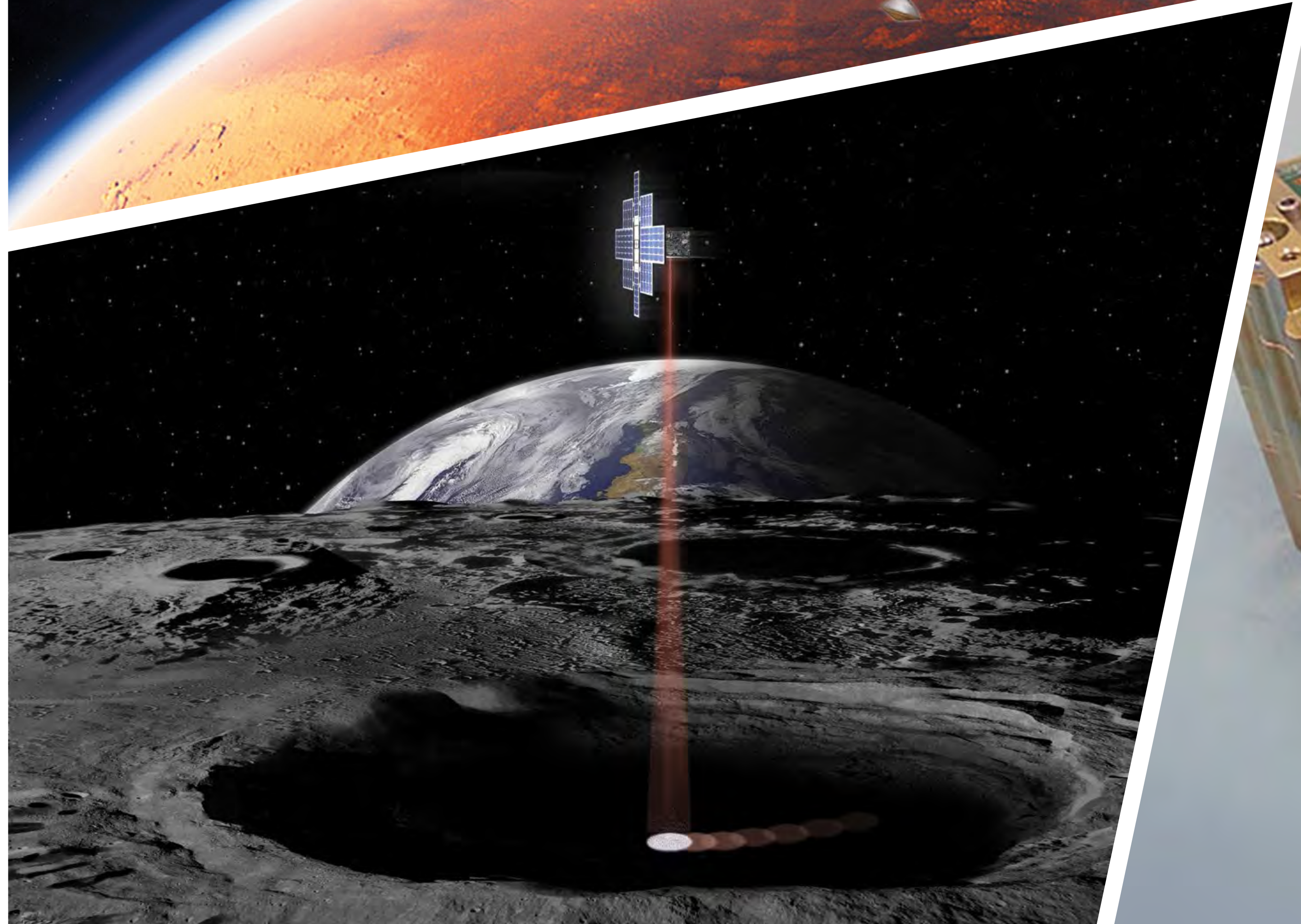
The ADAPT system, in preparation for a flight test of TRN, demonstrating how the LVS payload can help a spacecraft divert its course and make a smooth, pinpoint landing.

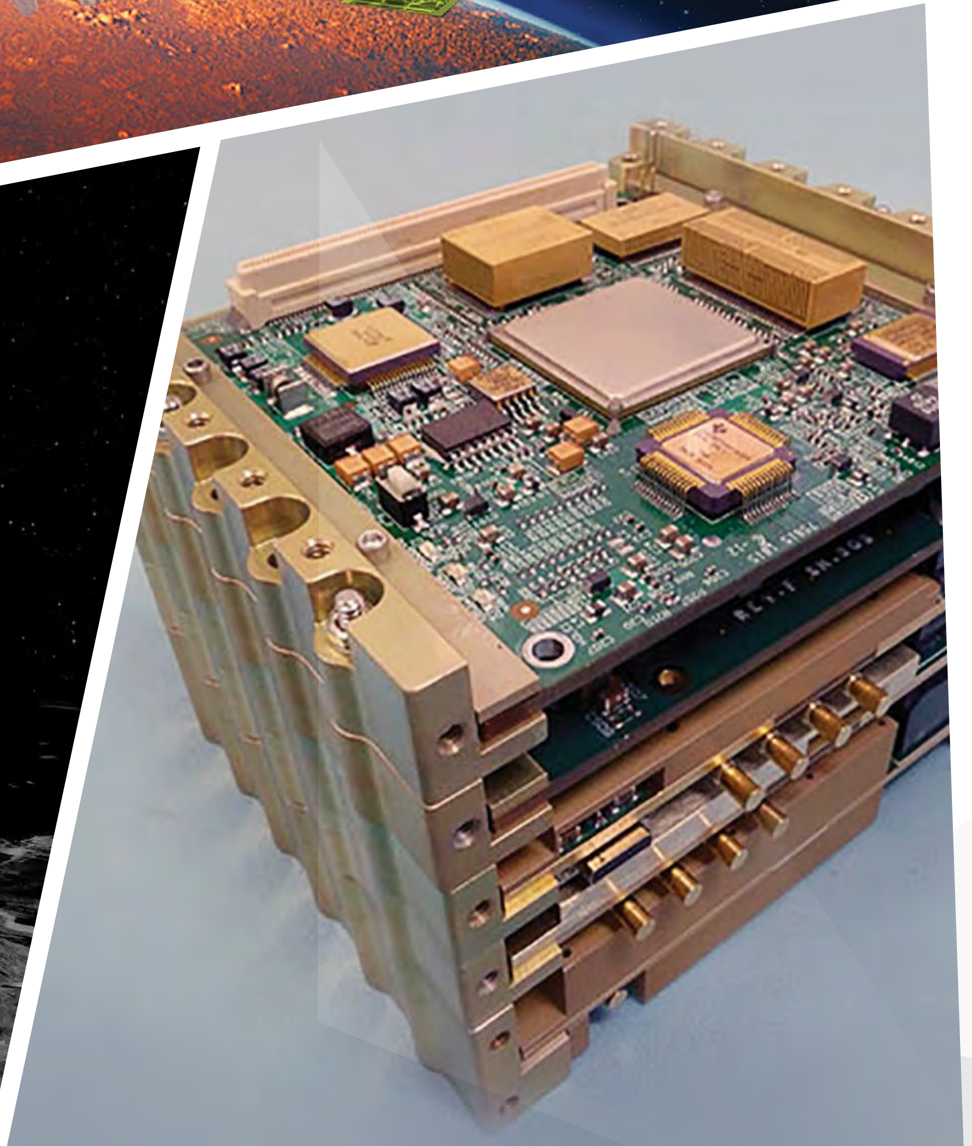


[A] Iris will be included in Morehead State University's CubeSat called Lunar IceCube, designed to search for water ice at a low orbit of only 62 miles above the surface of the Moon. **[B]** LunarH-Map will map hydrogen within craters and other permanently shadowed regions throughout the Moon's south pole. **[C]** Near-Earth Asteroid Scout will perform reconnaissance of an asteroid, take pictures and observe its position in space.



MarCO, the first CubeSats to be flown in deep space, will immediately transmit Mars lander InSight's entry, descent and landing information using the softball-size IRIS radio transponders.





SMALLER, LIGHTER, DEEPER SPACE COMMUNICATIONS

JPL's Iris technology, an X-Band transponder, is the first and only Deep Space Network (DSN) compatible transponder for small spacecraft. Iris's unique form factor of low volume, mass, and power would enable deep space command, telemetry, and navigation of small spacecraft and CubeSats.

This technology development began in 2013 and is expected to support a number of future missions, including JPL's INSPIRE, Lunar Flashlight, Near Earth Asteroid Scout, Lunar Ice Cube, LunarH-Map and CuSSP. In 2015, Iris was successfully delivered to the Mars CubeSat One (MarCO) project. The first interplanetary CubeSat mission, MarCO will support NASA's InSight mission to Mars scheduled for 2018.

Iris uses a hardware "slice" architecture and reconfigurable software and firmware enabling extension and adaptation to new capabilities. Among those now planned are: Radio Science support (atmospheric and media measurements and occultations, gravity fields, radars, and radio-meters); additional frequency bands (Ka-, S-, UHF); Disruption/Delay Tolerant Networking (DTN); proximity operations (at other planets such as Mars); Near Earth Network (NEN) compatibility; and Space Network (SN) compatibility.

In 2015, Iris was verified against the DSN recievers, demonstrating receiver sensitivity and standard transmission waveforms and coding schemes suitable for deep space operation with the DSN. Iris has also undergone environmental testing as part of the MarCO pre-launch campaign. In addition to a UHF receiver "slice" developed for MarCO, UHF, Ka-Band, and S-Band "slices" are in development to support command, telemetry, and radio science needs from various solar system bodies and locations.

Commercialization of Iris is now in progress to make the technology available to additional future missions.

[lower left] The Lunar Flashlight mission concept would examine the Moon's surface for ice deposits and identify locations where resources may be extracted **[lower right]** Iris Version 2 transponder is a low volume and mass, lower power and cost, software/ firmware defined telecommunications subsystem for deep space.

IRIS uses a hardware "slice" architecture and reconfigurable software and firmware enabling extension and adaptation to new capabilities.

READY, AIM, MEASURE: AUTOMATING SCIENCE ON MARS

AEGIS enables science targets to be hit on the first try by automatically identifying them through onboard image analysis and calculating a pointing that will center a ChemCam measurement on the desired target.

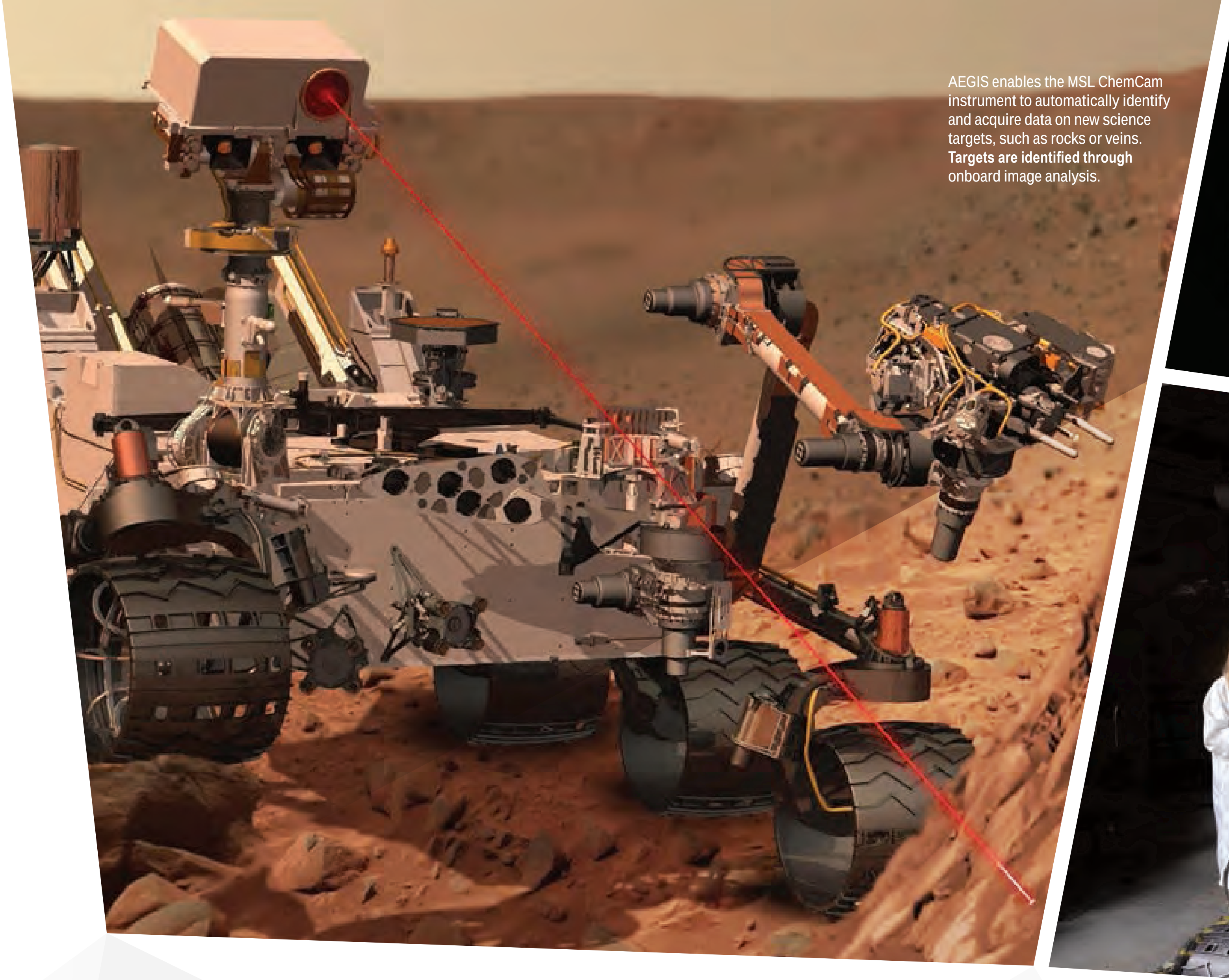
Selecting compelling science targets on Mars is a manual, time-consuming process. For the Mars Science Laboratory (MSL) rover's ChemCam that analyzes rocks using laser illumination, identifying and hitting these targets accurately can often require the rover to stay in place for several days while ground operators fine-tune pointing parameters.

JPL's Autonomous Exploration for Gathering Increased Science (AEGIS) intelligent targeting software enables ChemCam to acquire data on different types of rock targets and is especially valuable for acquiring data on fine-scale targets, such as veins or concretions, which are often of particular interest to the science team. AEGIS enables these targets to be hit on the first try by automatically identifying them through onboard image analysis and calculating a pointing that will center a ChemCam measurement on the desired target.

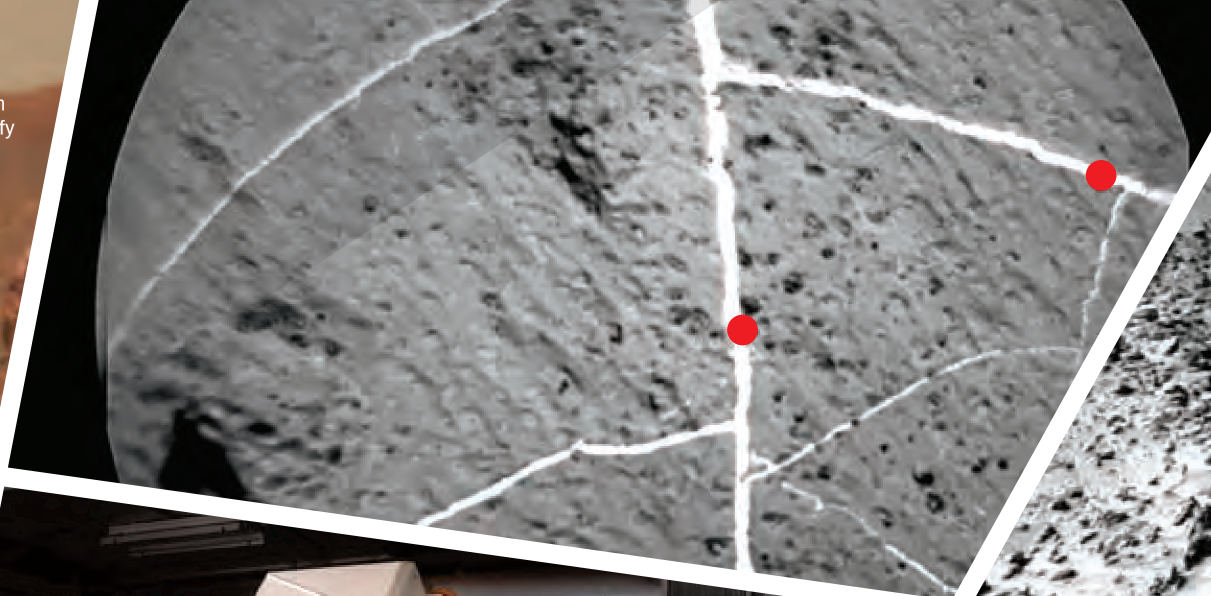
With AEGIS, the rover analyzes images onboard, detects and prioritizes science targets in those images, and autonomously obtains novel, high-quality science data of the selected targets within a few minutes, with no communication back to Earth required.

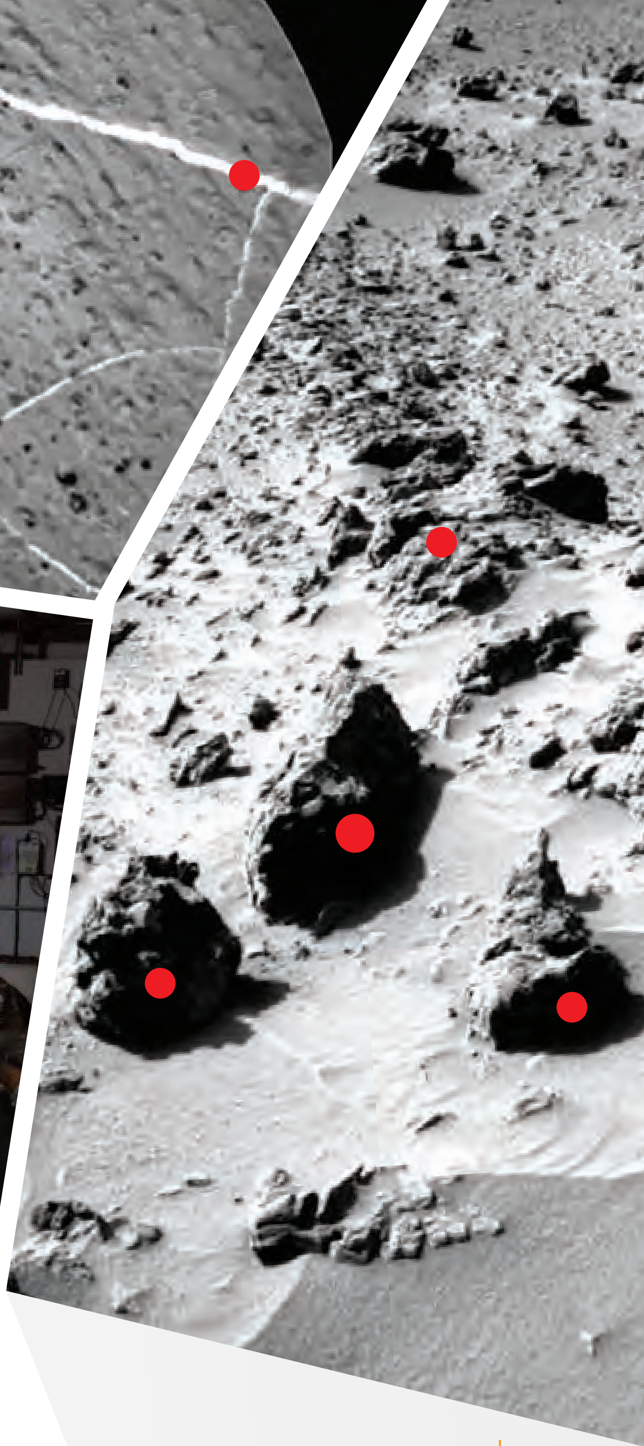
In 2015, AEGIS completed the MSL verification and validation (V&V) process and was uploaded to the MSL rover – named Curiosity – on Mars. It is expected to be ready for nominal operational use on Curiosity in Spring 2016.

JPL led the development of AEGIS and its infusion into the MSL mission. AEGIS was also previously used on the Mars Exploration Rover (MER) Mission Opportunity rover to select targets for the MER panoramic cameras. It is the first and only onboard software system to direct science collection through onboard data analysis for a NASA deep space mission. AEGIS was developed in partnership with Los Alamos National Laboratory and the Research Institute in Astrophysics and Planetology (IRAP)in France.



AEGIS enables the MSL ChemCam instrument to automatically identify and acquire data on new science targets, such as rocks or veins. **Targets are identified through onboard image analysis.**





[above] AEGIS Principal Investigator Tara Estlin operating the MSL VSTB testbed. **[top]** Image shows the results of AEGIS identifying veins in its initial use onboard Curiosity. **[right]** AEGIS identifying large dark rocks in an early mission image. The red markers in these images show the top targets that AEGIS selected for measurement with ChemCam.

[A] USAID Search and Rescue Team USA-1 prepares FINDER for use in Kathmandu. [B] The NASA/JPL developed FINDER is a portable radar that detects buried victim heartbeat and respiration. [C] Rescuer's assist a victim after the Nepal earthquake in April 2015. [Photo credit: EPA Narendra Shrestha].

FINDER sends a low-powered microwave signal — about one-thousandth of a cell phone's output — through rubble and looks for changes in the reflections of those signals coming back from tiny motions caused by victims' breathing and heartbeats.

Urban Search and Rescue Specialist carries FINDER to Virginia Task Force 1's training rubble pile for testing.

HEARING HEARTBEATS THROUGH THE RUBBLE

A small, suitcase-sized device called FINDER helped rescue four men in one of the hardest-hit areas rattled in 2015 by the 7.8 magnitude earthquake in Nepal that killed over 8,000 people and injured more than 21,000. The NASA technology detected the men's heartbeats even though they were buried under about 10 feet of brick, mud, wood and other debris.

FINDER, which stands for Finding Individuals for Disaster and Emergency Response, is a collaborative technology developed between JPL and the Department of Homeland Security's Science and Technology Directorate. FINDER detects the small motions using low-powered microwave radio signals and algorithms similar to those that JPL uses to measure the orbits of satellites at Jupiter and Saturn, or changes in Earth's surface from orbiting satellites. It then displays the detected heart and respiration rates and a reliability score. FINDER's software can distinguish between the heartbeats of a human and those of animals or mechanical devices.

There are many potential uses in medicine as well: A device based on FINDER could monitor the vital signs of someone who is trapped in a car or quarantined with an extremely contagious disease such as Ebola. In these situations, first responders could measure a patient's heartbeat without having to physically touch them. The next generation of this technology could combine FINDER with robotics and even small autonomous flying vehicles to get closer to victims and examine a wider area.

"NASA technology plays many roles: driving exploration, protecting the lives of our astronauts, and improving —even saving— the lives of people on Earth," said David Miller, NASA's chief technologist at NASA Headquarters in Washington. "FINDER exemplifies how technology designed for space exploration has profound impacts to life on Earth."

FINDER has previously demonstrated capabilities of finding people buried under up to 30 feet of rubble, hidden behind 20 feet of solid concrete, and from a distance of 100 feet in open spaces. On May 7, 2015, a new prototype of FINDER was demonstrated at the Virginia Task Force One Training Facility in Lorton, VA. Virginia Task Force One, who responded to the Nepal earthquake as USA-1, provided testing assistance and brought their real-life disaster response experience to assist the JPL engineers developing FINDER. Two companies who have licensed FINDER are manufacturing units for search and rescue teams around the world.

ROBOSIMIAN relies on conventional elements arranged to approximate the generalized limbs of simians. These limbs, and the novel hands at the end of them, are capable of opening up many solutions unavailable to more conventional designs such as humanoids and rovers.

Inspired by the high "operational flexibility" of monkeys and apes, JPL developed the RoboSimian robot in response to DARPA's Robotics Challenge, a competition of robot systems and software teams vying to develop robots capable of assisting humans in responding to natural and man-made disasters. Having qualified as a Finalist in the Challenge Trials in December 2013, RoboSimian joined a field of twenty-four teams from around the world in June 2015 for the Robotics Challenge Finals.

RoboSimian was specifically intended as the progenitor of a design that could be deployed within the next five years. Its simian limbs, and the novel hands at the end of them, are capable of both mobility and manipulation, opening up many solutions unavailable to more conventional designs such as humanoids and rovers.

RoboSimians's unique system requires advanced algorithmic software, in particular the planning software that calculates the proper motion of all 28 joints in its limbs. Human operators direct the entire system in a supervised autonomy arrangement under which the operator can specify behaviors that the robot then executes itself.

After the two-day competition, RoboSimian finished 5th in the overall standings of 24 teams.

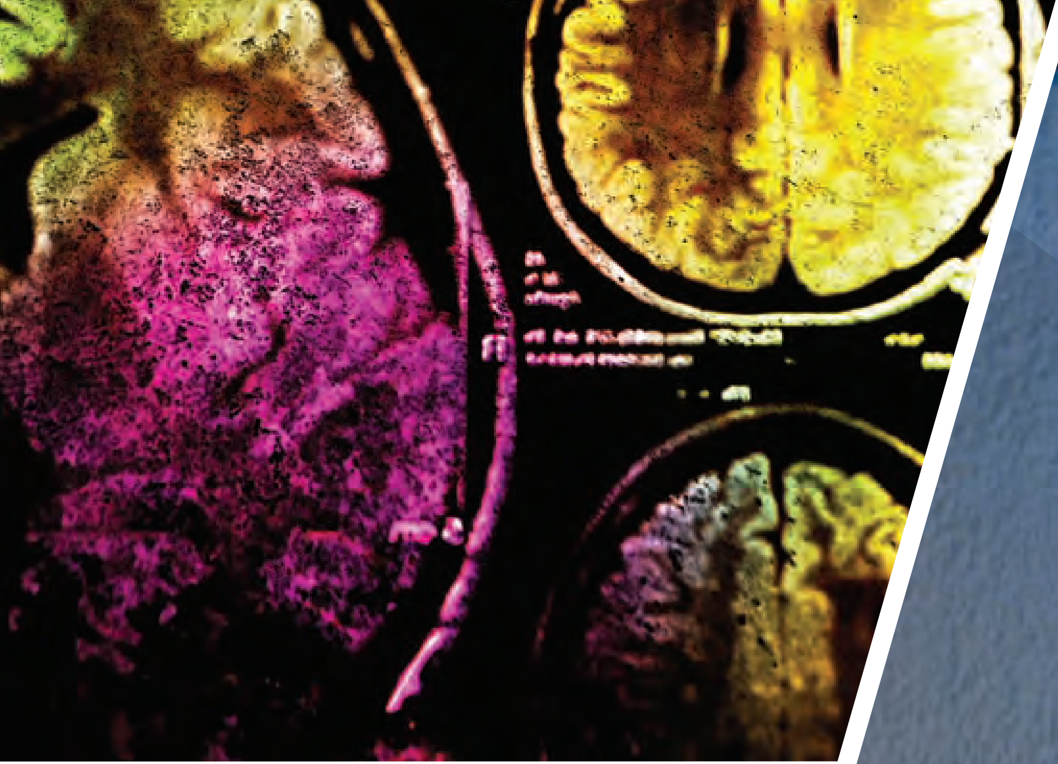
The Robo-Simian team took pride in being one of the two most consistent teams over the two days and being the only robot not to have fallen during the competition.

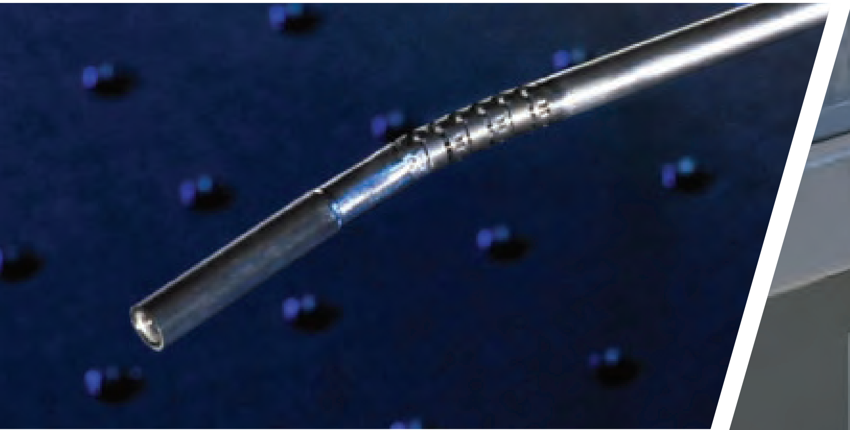
Now retired from competition, the two RoboSimian robots built at JPL have been repurposed, most notably to investigate the assembly of orbital structures from deployable trusswork. In addition, another RoboSimian is under construction with General Dynamics for use by the Army Research Lab's Robotics Collaborative Technology Alliance, which will provide the robot to university researchers within the Alliance.

RoboSimian was developed in partnership with the University of California, Santa Barbara, Caltech, and Stanford University.

A LITTLE "ROBOTIC" MONKEY BUSINESS

Like apes and monkeys, RoboSimian can use its four limbs to maneuver heavy objects or progress through dangerous environments.





[top] This technology will allow surgeons to perform procedures quicker, safer and more precisely, resulting in better outcomes and lower costs for both hospitals and patients. [above] A tiny, electronic, high-definition 3-D camera mounted on the tip of the endoscope. [right] Laboratory prototype of MARVEL, one of the world's smallest, steerable 3-D cameras.

ROCKET SCIENCE, BRAIN SURGERY, AND THE **INSTRUMENTS** OF **CHANGE**

JPL, in collaboration with the Skull Base Institute (SBI), is developing the next generation of endoscopic tools creating "super instruments" that will bring together sweeping advancements in digital imaging, 3D endoscopy, heads-up displays, and smart micro/nano technology.

As good as a state-of-the-art, high-definition endoscope is for examining the inner parts of the body, in the head and neck regions, it can only give surgeons a flat, 2D view at a fixed angle – zero, 30 or 70 degrees created by physical shaping of the objective end.

Now, with the Multi-Angle Rear-Viewing Endoscopic Tool (MARVEL), the surgeon will be able to use an instrument that can continuously sweep over 120 degrees, allowing a 3D view of the operating field from different angles. This is made possible by implementing the focal plane array immediately behind the 3D imaging lens system, which is connected to the endoscope stem via a bending section that can be actuated at the proximal end.

MARVEL includes a tiny, electronic, high-definition camera mounted on the tip of the endoscope. Although miniature 2D cameras exist to suit this application, this is the first time a 3D imaging camera has been developed at this size. The technology to achieve 3D imaging in such a space-constrained device was developed using a time-multiplexed imaging technique that employs complementary multi-band pass filter apertures.

The image transmitted from MARVEL can appear on 3D display monitors similar in appearance to those used with conventional endoscopes. These 3D displays can give the surgeon superior visibility, depth perception, and the ability to place surgical tools with the utmost precision. The benefits are significant: Seeing the tumor in 3D and in high definition will allow surgeons to perform procedures more quickly, safely, and precisely, resulting in better outcomes and lower costs for both hospitals and patients.

MARVEL has won the Federal Laboratory Consortium for Technology Transfer (FLC) 2015 Outstanding Technology Development Award and is regarded as an important advancement in medical technology. For NASA, the technology will offer a new capability to perform proximity stereo imaging for planetary exploration.

MARVEL is developed in partnership with the Skull Base Institute.

Seeing the tumor in **3D** and **HIGH DEFINITION** will allow surgeons to perform procedures quicker, safer, and more precisely, resulting in better outcomes and lower costs for both hospitals and patients.

DSAC will transform the traditional two-way paradigm of deep space tracking to a more flexible, efficient, and extensible one-way tracking architecture.

BETTER CLOCKS, BETTER NAVIGATION, BETTER SCIENCE

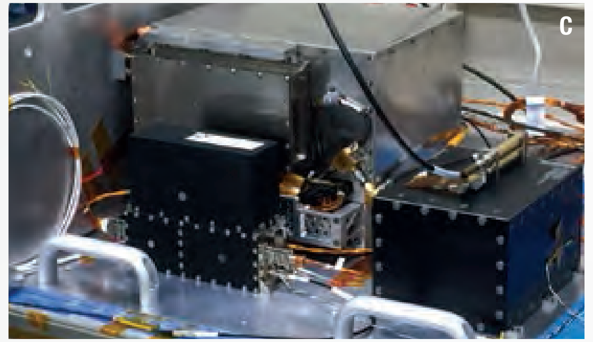
As the saying goes, timing is everything. The Deep Space Atomic Clock (DSAC), a miniaturized and stable mercury ion atomic clock, could enable autonomous radio navigation for a spacecraft's time-critical events such as orbit insertion or landing, promising higher confidence in mission operations. It is expected to improve the precision of deep-space navigation, enable more efficient use of tracking networks, and significantly enhance radio science at Europa, Mars, and other celestial bodies.

Ground-based atomic clocks have long been the cornerstone of most deep-space vehicle navigation because they provide root data necessary for precise positioning. DSAC will deliver the same stability and accuracy for spacecraft exploring the solar system. This new capability could forever change the way we conduct deep-space navigation – by eliminating the need to "turn signals around" for tracking. Much the same way modern Global Positioning Systems, or GPS, use one-way signals to enable terrestrial navigation services, DSAC will provide the same capability in deep-space navigation. The one-way deep space navigation enabled by DSAC uses the existing Deep Space Network more efficiently than the current two-way system, thus expanding the network's capacity without adding any new antennas or their associated costs. DSAC will transform the traditional two-way paradigm of deep space tracking to a more flexible, efficient, and extensible one-way tracking architecture.

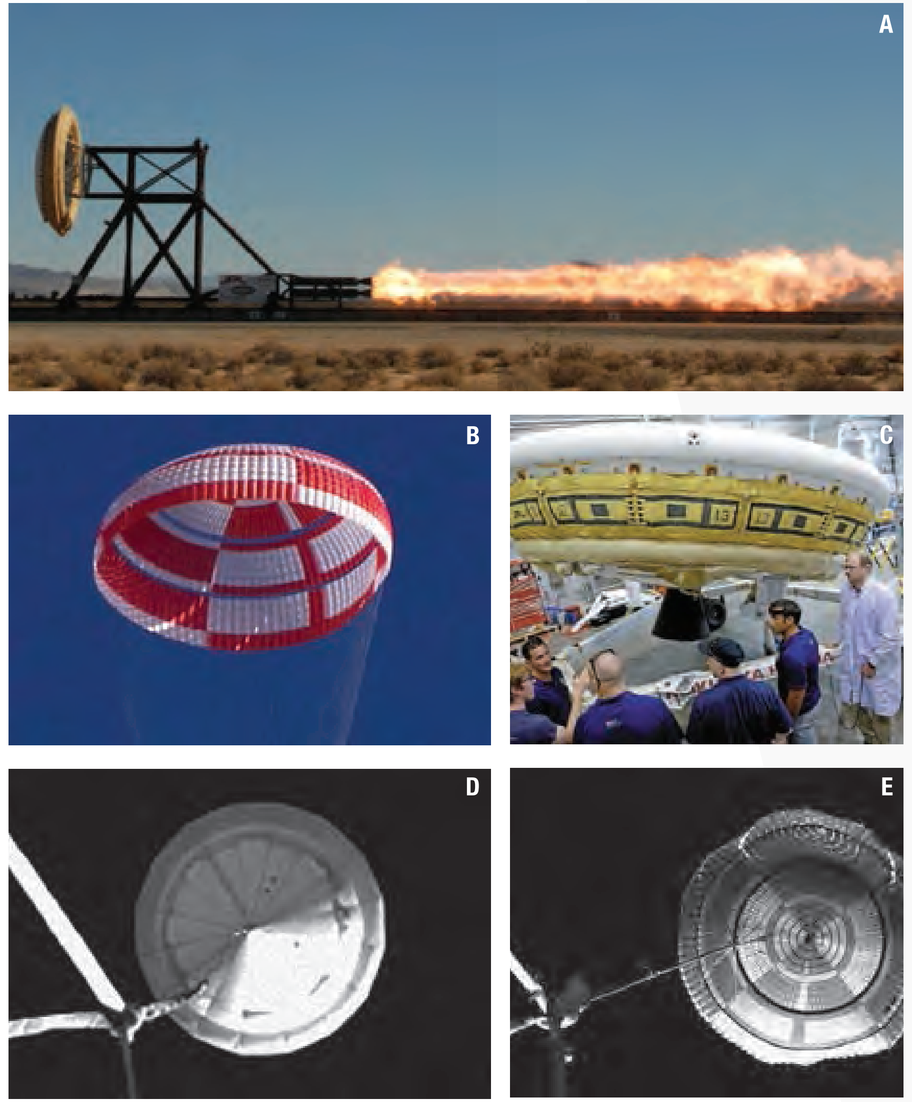
DSAC's benefits extend to human exploration of the solar system. On-board radio navigation combined with the tracking efficiencies derived by using DSAC are enabling robust, safe navigation for human exploration of deep space.

DSAC's development includes a one-year flight test in low-Earth orbit in early 2017 to validate the clock's unprecedented stability and demonstrate its precision one-way radio navigation. It will be a hosted payload on the Surrey-US Orbital Test Bed satellite that will be launched as part of the U.S. Air Force's Space Test Program 2 mission aboard a SpaceX Falcon Heavy rocket.

The NASA DSAC Technology Demonstration Mission is a year-long experiment in space where the DSAC payload will be hosted on the Surrey-US Orbital Testbed Spacecraft.



[A] A potential application for Deep Space Atomic Clock would be to enhance the timing performance of future GPS satellites. [B] Titanium housing, when complete, forms the vacuum tube that contains the mercury ion trap. [C] The DSAC payload (consisting of the DSAC demonstration unit, ultra stable oscillator, and GPS receiver) is being prepared for testing. [D] Another future use for DSAC would be to use the technology to help investigate possible undersea oceans within Jupiter's moon, Europa.



[A] Rocket sled testing of the SIAD-R going 220 mph at the Naval Air Weapons Station China Lake test track in October 2012. **[B]** Supersonic Ringsail parachute deployed and at full load during a ground test at the Naval Air Weapons Station China Lake. **[C]** The US Navy's vehicle recovery dive team reviews the details of the LDSD Supersonic Flight Development Test (SFDT) vehicle prior to its flight in Hawaii in June 2015. **[D]** Supersonic Ballute in high altitude flight at Mach 27 in June 2015. **[E]** Supersonic Ringsail parachute at inflation, shortly before failure, in the June 2015 SFDT flight.

With the Pacific ocean in the background, the STAR-48 solid rocket pushes the SFTD vehicle from its balloon launch at 120, 000 feet up to 190,000 feet moving at 4 times the speed of sound in preparation for SIAD, ballute and super-sonic parachute testing in June 2015.

THE DRAG OF LANDING A **HOUSE** ON **MARS**

How do you to get the next generation of landers—the precursors to human missions—safely to the surface of Mars? How do you create enough drag to decelerate a spacecraft to a safe touchdown speed in that planet's thin, shallow atmosphere?

NASA's Low-Density Supersonic Decelerator (LDSD) Project is developing and testing the next generation of supersonic aerodynamic decelerators for planetary entry enabling delivery of larger landed payloads to the surface of Mars.

On June 8, 2015, the project conducted the second high-altitude Supersonic Flight Dynamics Test, following an initial 2014 shakeout test. This second test included a 6 m diameter Robotic-class Supersonic Inflatable Aerodynamic Decelerator (SIAD-R), a 4.4 m diameter trailing ballute (balloon parachute), and a new 30.5-meter diameter supersonic Ringsail parachute.

The SIAD-R is a lightweight inflatable torus attached around the rim of the entry vehicle which, upon deployment, increases the vehicle's cross-sectional area, thereby generating additional aerodynamic drag and deceleration. The deployment was executed successfully, with the SIAD-R demonstrating excellent performance in aerodynamic drag and stability.

At Mach 2.8, the ballute was deployed. Like the SIAD-R, ballute, performance was excellent. The ballute was then used as a pilot device for deployment of the supersonic Ringsail parachute. Initial inflation of the parachute proceeded nominally; however, at or near the moment of full inflation, the parachute failed due to tear in the canopy.

High-resolution and high-speed video recordings of the parachute inflation, along with other instrumentation to characterize performance, captured a wealth of data for ongoing investigation into the potential cause of the parachute anomaly. This test has validated performance of the SIAD-R and ballute for future use at Mars. In addition, observing the parachute anomaly in this highly instrumented test provides essential data for improving the design and robustness of future Mars parachutes.

... developing and testing the next generation of supersonic aerodynamic decelerators for planetary entry, enabling delivery of larger landed payloads to the surface of Mars.

METALLIC GLASS
CHILLING THE INDUSTRY

The demanding applications put on JPL spacecraft and rovers often require new materials that behave in ways other materials cannot. Researchers at JPL are working on new materials and manufacturing technologies that can potentially solve many of the problems faced by future missions. One new material in particular, called bulk metallic glass —also known as BMG or amorphous metals— has particularly interesting possibilities for making a variety of movable structures for spacecraft.

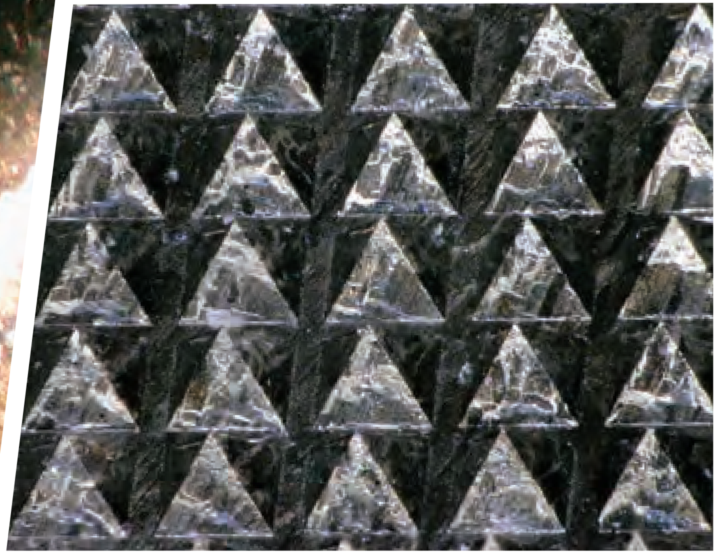
A BMG is a metal with the structure of glass, but it is neither brittle nor transparent. The new metal alloys developed at JPL, based in titanium, zirconium and copper, can be cooled so fast from their molten state that they freeze as a glass, giving them an amorphous arrangement of atoms similar to a liquid. The parts take on a lustrous metal appearance and possess new and exciting properties for use in spacecraft.

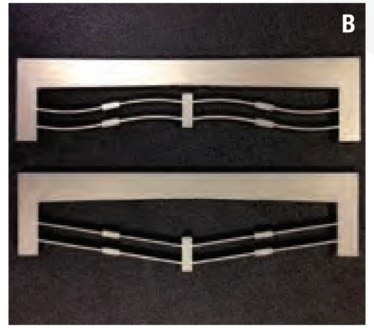
The unique atomic arrangement of BMGs imparts them with astounding mechanical properties. BMGs typically will exhibit twice the strength of titanium, the hardness of tool steel, wear resistance similar to ceramics, the flexibility of plastics, and the low melting temperature of aluminum. Unlike most high-performance metals, BMGs can be injection-molded like plastic using commercial machines, allowing for incredible complexity and low-cost in cast parts. Although these properties are very exciting, understanding how to develop and use the materials in common applications has been elusive. Researchers at JPL are solving these problems by developing new BMG alloys and composites, designing new manufacturing technologies to make parts, prototyping and rigorously testing spacecraft hardware, and working with industry to commercialize the results. Douglas Hofmann at JPL received the 2012 Presidential Early Career Award for Scientists and Engineers, given by President Obama, in connection with this work.

JPL has already had success with developing castable gears and gear components that exhibit excellent wear resistance at cold temperatures without the use of liquid lubricants. They have also developed BMG flexures, compliant mechanisms, spacecraft debris shielding, new carbon-fiber/BMG composites, mechanical inserts, microdevices for spacecraft propulsion, advanced coatings, and even the legs for a wall-climbing robot. JPL researchers have also been actively developing BMG technologies and spinning them off to industry to be commercialized. Such materials could be used for medical devices, cars, laptops and other applications.

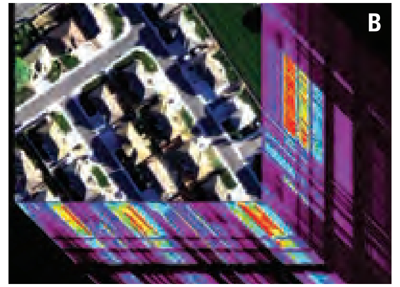
The unique atomic arrangement of **BMG**s imparts them with astounding mechanical properties.

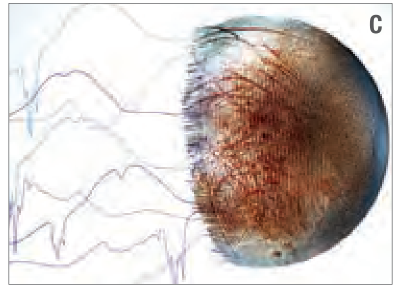
A cast bulk metallic glass spur gear directly out of a mold.





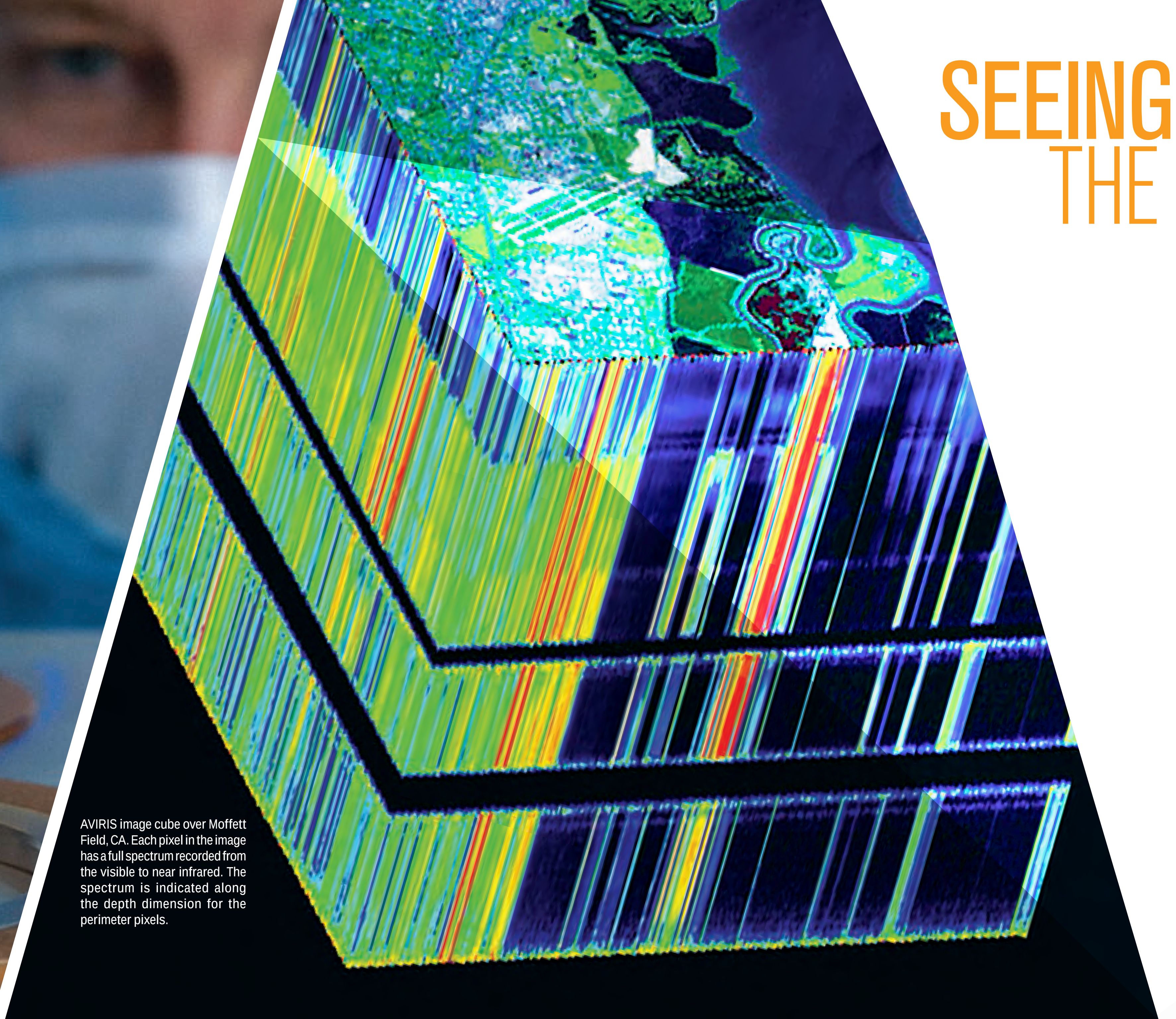
[above] Bulk metallic glasses are optimal for fabricating micro devices such as these 100 micron wide pyramids fabricated through thermoplastic forming. **[A]** President Obama with the 2012 PECASE winners, including Dr. Douglas Hofmann. **[B]** Injection-molded bulk metallic glass bistable compliant mechanisms showing the elastic storage potential of these high-flexibility metals. **[C]** A planetary gearbox comprising bulk metallic glass gears fabricated at JPL. These gearboxes can operate without any liquid lubricant, which makes them attractive for space applications.





[A] 'Shaped-groove' grating used on the Moon Mineral Mapper, one of two instruments that NASA contributed to India's first mission to the Moon, Chandrayaan-1. **[B]** AVIRIS image cube shows the volume of data returned by the instrument. The sides are pseudo-color, ranging from black and blue (low response) to red (high response). **[C]** The Mapping Imaging Spectrometer for Europa (MISE) is enabled by JPL components and decades long investments and will produce maps of organic compounds, salts, hot spots, and ices to answer key science questions about Europa's ocean and its habitability.

JPL researcher fabricating triple blaze gratings in the Microdevices Laboratory cleanroom.



AVIRIS image cube over Moffett Field, CA. Each pixel in the image has a full spectrum recorded from the visible to near infrared. The spectrum is indicated along the depth dimension for the perimeter pixels.

SEEING THE LIGHT TO UNVEIL THE WORLDS AROUND US

Imaging spectroscopy, a technique that captures a spectrum for every pixel in an image, is a powerful tool for understanding the composition of planetary surfaces and atmospheres. JPL created this field and has been at its forefront for decades, and has built many imaging spectrometers, both for looking at other planets and our own Earth.

JPL has excelled in this field due in large part to the capability of designing and fabricating custom diffraction gratings. The diffraction grating, a key component of any imaging spectrometer, has a periodic structure that separates light into a spectrum, with each beam traveling in a different direction.

JPL has developed and qualified new processes to enable the fabrication of high-performance, shaped-groove diffraction gratings out of durable, radiation-hard substrates. Such processes push the limits of electron-beam lithography, and allow JPL to remain at the frontier of delivering compact, higher performance imaging spectrometers.

JPL's imaging spectrometer missions include the Moon Mineralogy Mapper (M3), responsible for detecting water on the Moon, as well as the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) that has been in operation for more than 25 years and studies the molecular absorption and particle scattering signatures of Earth's surface and atmosphere.

Currently, JPL is building a new instrument called the Mapping Imaging Spectrometer for Europa (MISE), which was recently selected as part of the payload for the planned Europa Multiple Flyby Mission, expected to launch in 2022. This imaging spectrometer would operate in a high-radiation environment and would be able to withstand high-temperature thermal cycles for planetary protection.

JPL has developed and qualified new processes to enable the fabrication of high-performance, shaped-groove **DIFFRACTION GRATINGS...**

ROCKETEERS, ROCKET FUEL, AND BEYOND

Take a tenth of a kilogram of rocket fuel, use it in your favorite rocket engine and measure how long you can sustain a thrust of one newton. It is a measure of how efficiently your rocket is using its propellant. That time, measured in seconds, is the key figure of merit for rocketeers, such as Dan Goebel, who literally wrote the book on Electric Propulsion.

For typical mono-propellant chemical thrusters this value is around 220 seconds. The best chemical rockets use liquid hydrogen and liquid oxygen to extend this time to 450 seconds. But that's nothing compared to what electric rockets, such as the ion thrusters on JPL's Deep Space 1 and Dawn missions, can do. These ion rockets extend this time to an incredible 3,000 seconds, making them nearly ten times more efficient than conventional rocket engines.

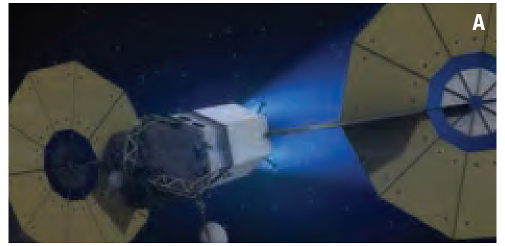
So what can you do with all this fuel efficiency? A lot, it turns out. The Dawn mission used it to rendezvous with the two heaviest main belt asteroids Vesta and Ceres, a feat that would be effectively impossible without ion propulsion. The Discovery mission Psyche, competitively selected in 2015 for a Step 2 Phase, is proposing to use it for an inaugural visit to a metal asteroid in the main belt. The proposed Asteroid Redirect Mission (ARM) would scale up the thrust level of the Dawn ion propulsion system by a factor twenty and use that capability to potentially return a multi-ton boulder from a near-Earth asteroid. Scale up the ARM system by another factor of three to five and you have a system that Human Exploration mission designers are studying as an integral part of the Evolvable Mars Campaign to ultimately send people to Mars.

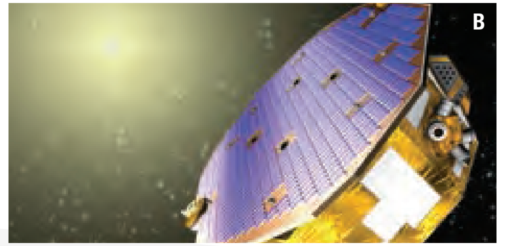
In addition to being incredibly fuel efficient, ion propulsion can provide exquisite control. The electrospray thrusters on the ST7 spacecraft launched in 2015 provide a thrust level a thousand times lower than the already very low thrust of the Dawn ion thrusters. All eight of the thrusters on ST7 have been successfully checked out.

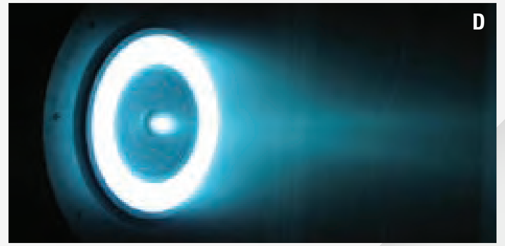
All this activity in electric propulsion at JPL has not gone unnoticed. Dan Goebel was elected to the National Academy of Engineering in 2015 and John Brophy was awarded the Ernst Stuhlinger Medal for Outstanding Achievement in Electric Propulsion also in 2015.

The Dawn mission used it to rendezvous with...asteroids Vesta and Ceres, a feat that would be effectively impossible without **ION PROPULSION**.

Artist's concept of Dawn firing its ion engine as it approaches Ceres. The xenon ions glow with blue light. It launched in 2007 to orbit the large asteroid Vesta and the dwarf planet Ceres.



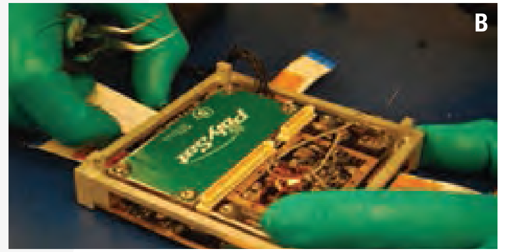


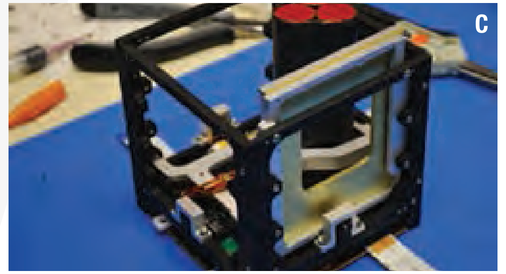


[A] Artist concept of the spacecraft for the Asteroid Redirect Mission (ARM) using its high power ion propulsion system to return a multi-ton boulder from a near-Earth asteroid. **[B]** Artist illustration of the proposed ST-7 spacecraft that includes two clusters of four micro-newton thrusters. **[C]** Launched in 1998, the Deep Space 1 spacecraft, pictured in JPL's thermal-vacuum chamber, demonstrated the first use of ion propulsion in deep space on a NASA mission, paving the way for its use on the Dawn mission. **[D]** The latest in high-power Hall thruster technology undergoing development testing for use on the proposed ARM mission. **[E]** Dan Goebel with the 20-kW ion thruster developed for the Jupiter Icy Moons Orbiter Mission.

Artist's conception of IPEX CubeSat in Earth Orbit.

SMALL SAT SENDS THE "RIGHT" IMAGES FOR EARTH SCIENCE





[A] IPEX CubeSat. [B] Cal Poly Intrepid system board used in CubeSat. [C] IPEX structure showing batteries above system board. [D] TextureCam classification of clouds. [E] Salience recognition (of exceptional or high-contrast features) of lakes in Ngari Prefecture, China, prioritized for downlink.

The Intelligent Payload Experiment (IPEX) CubeSat's software and algorithms can sift through data, looking only for the most important images that the scientists urgently need on the ground.

This method is designed to speed delivery time of critical data products from days to minutes. IPEX will enable future missions to recognize science events such as flooding, volcanic activity, and wildfires, enabling end users near real-time access to data.

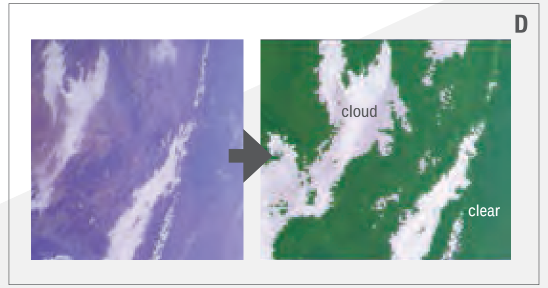
IPEX launched in December 2013 for a six month mission, achieved its success criteria in three months, and flew for 14 months completing operations in 2015.

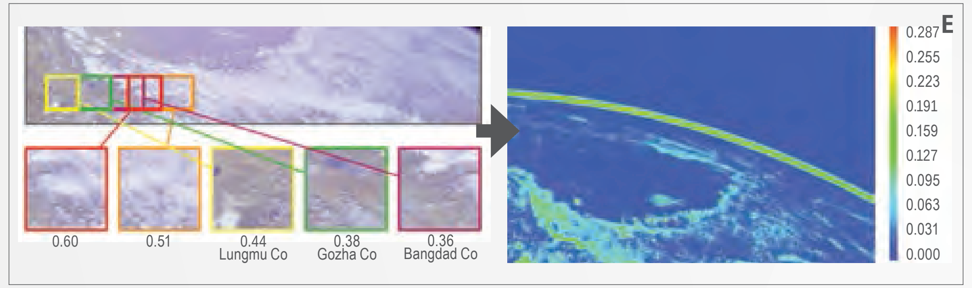
IPEX validated over 31,000 image products generated with near-continuous autonomous operations with 100% reliability. IPEX also validated direct broadcast, autonomous science, and product delivery technologies supporting Technology Readiness Level (TRL) advancement relevant to future climate science measurements such as the Intelligent Payload Module (IPM) targeted for the proposed Hyperspectral Infrared Imager (HyspIRI) Earth Science Decadal Survey mission concept.

IPEX also demonstrated Web-based autonomous payload operations of event/over-flight-based product generation and enhanced NASA/university partnerships to engage students and faculty by flying technology payloads on small satellites. Feature detection, classification, and machine learning algorithms were run with a 100% success rate and in addition to Earth missions like HyspIRI, will be infused into future, beyond-LEO CubeSat autonomous processing missions.

IPEX was developed in partnership with Cal Poly State University, San Luis Obispo.

This method is designed to speed delivery time of critical data products from days to minutes.





GECKO ADHESIVE PLUS ZERO-GRAVITY EXPERIMENTS

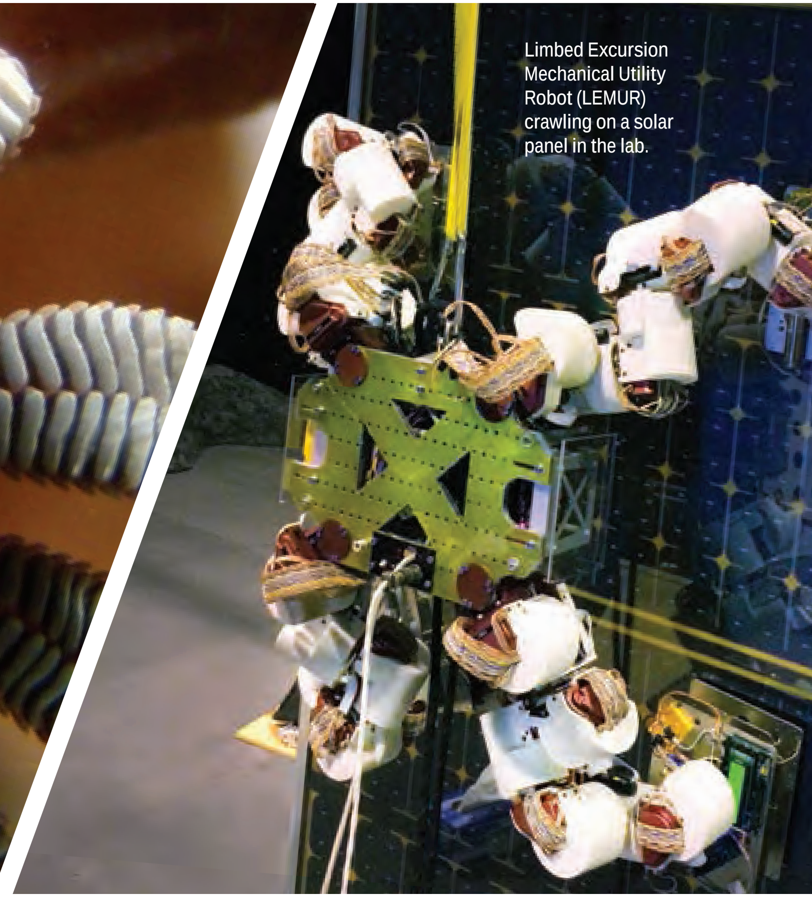
Reliably grappling objects — be they satellites or space stations — is critical to our future in space. A bad rendezvous would cost much more than any NFL fumble, as decades of dreams and planetary samples could tumble into the abyss.

Mechanical grasping often relies on the target's preexisting "handle" features. Without these, if the object is larger than the gripping device, capturing it becomes quite challenging. Such problems can be solved with adhesives. Traditional chemical adhesives, such as tapes and glues, are capable of strong bonds, but they aren't reusable and often fail in the harsh environment of space. Most tapes require firm pressure to adhere, and if the bond is too weak, the target won't stick around for long. Tapes also collect dust and debris, their stickiness degrades quickly between the first and second use, and cannot be cleaned easily. Though glues can create strong bonds, they will permanently fail once broken. To employ the simplicity of adhesive grappling while circumventing these issues, JPL looks to nature and party balloons.

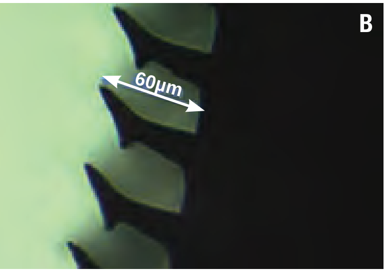
The animal kingdom's best climber is the gecko. On a gecko's toes are millions of microscopic hairs which adhere using weak Van der Waals forces. With enough hairs these forces become significant, holding up to 20 times the gecko's weight. Geckos can turn these forces on and off in a few milliseconds and stick with a very light touch. Using JPL's microdevices laboratory and rapid prototyping facilities, JPL researchers fabricated sheets of a reusable "gecko-like" material capable of supporting loads over 50-Newtons with 10 square centimeters of contact. JPL's synthetic gecko toes work well on smooth surfaces commonly used on spacecraft – fiberglass, aluminum, Mylar, and solar panels. To boost reliability and strength, JPL combined gecko adhesives with electrostatic adhesion. When a balloon picks up charge (i.e., by rubbing it on a wool sweater) it clings to surfaces – rough or smooth. JPL researchers generate a similar, stronger force by charging a high voltage directly behind the gecko hairs with a battery. The gecko adhesive and electrostatic forces complement each other, creating a net adhesion that is stronger than its parts.

JPL has put these adhesives to work on a flat plate gripper, a curved surface gripper, and two palm sized robots: one modeled after an inchworm, and the other capable of agile driving with a set of adhesive flap wheels. For 2015, JPL sought to validate the power and reliability of grappling and driving on a suite of targets in microgravity using NASA's micrograviy-gravity parabolic aircraft. Meter-scale analogs for an aluminum rocket body (the most common piece of orbital debris) and a spherical pressure vessel were successfully grappled and driven upon. A 220-pound (100-kilogram) flat aluminum plate was captured, reoriented, and released. Robots successfully navigated surplus solar panels. These technologies could be used in future space inspection, assembly, servicing, and repair missions. Based on these successful demonstrations, gecko-adhesive devices are planned to be sent to astronauts aboard the International Space Station for further testing in the spring of 2016. This technology was developed in partnership with Stanford University.

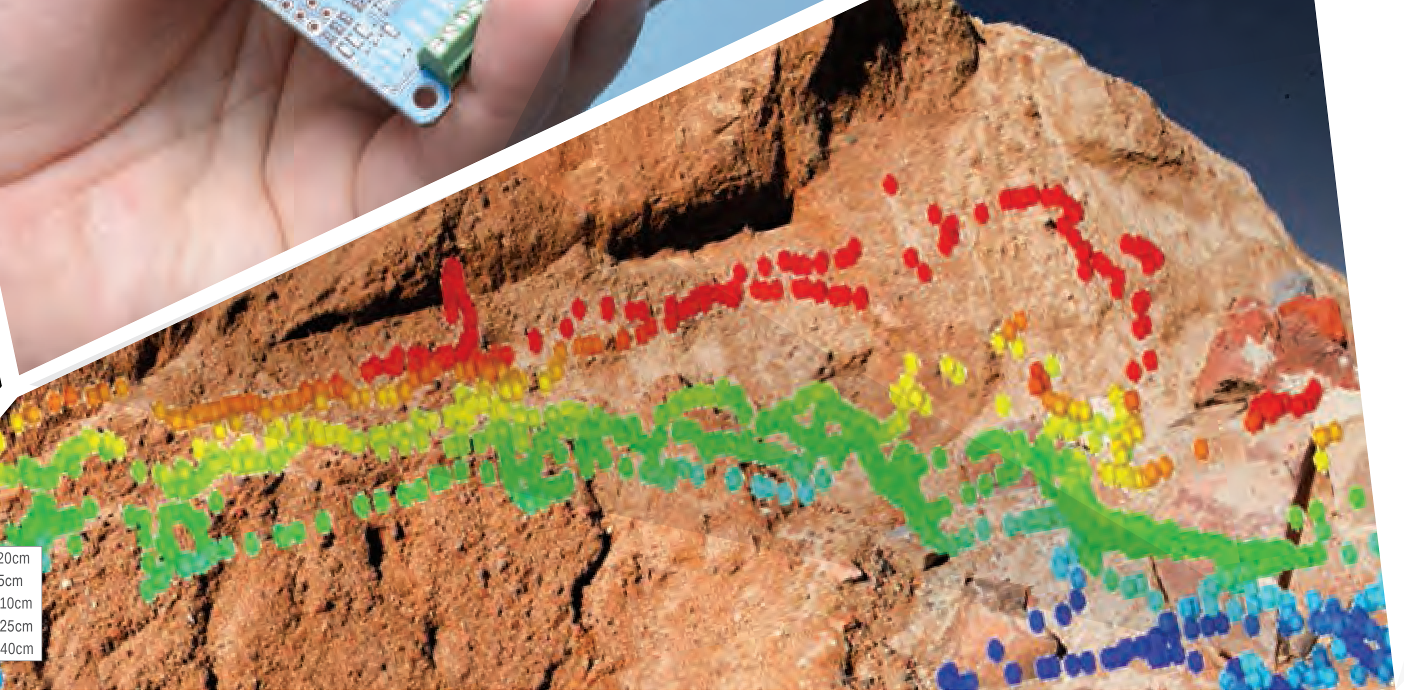
JPL researchers fabricated sheets of a reusable **"GECKO-LIKE"** material capable of supporting loads over 50-Newtons with 10 square centimeters of contact.



[top left] Principal Investigator Aaron Parness of NASA's JPL and the Stanford University team flew several gecko adhesive based experiments on NASA's zero gravity aircraft during the Aug 2015 campaign. **[top center]** JPL researchers were inspired by gecko feet, such as the one shown here, in designing a gripping system for space. Just as a gecko's foot has tiny adhesive hairs, the JPL devices have small structures that work in similar ways. [image credit: Wikimedia Commons]. **[A]** Team member Christine Fuller is grappling a free-floating 1-meter diameter aluminum cylinder with a gecko-adhesive enabled gripper. **[B]** Microscopic image of gecko-like material fabricated in the Microdevices Lab. **[C]** This artist's concept shows how a future robot called LEMUR (Limbed Excursion Mechanical Utility Robot) could inspect and maintain installations on the International Space Station. The robot would stick to the outside using a gecko-inspired gripping system.



The artist illustration shows how data can be collected as a swarm of CubeSats approach a body, pointing at random orientations.



[top] Commercial low-cost CMOS inertial measurement unit (IMU) developed for gaming platforms —can track their own orientation (theta, phi)— is coupled to a low cost CMOS LIDAR system to measure range. **[above]** Shown is a JPL Mars yard demonstration of collected laser range (LIDAR) measurements using a CMOS IMU. The IMU orientation data would be used to create a map and be combined with data from other remote sensors such as terahertz detectors, Hyperspectral imagers, and LIDAR — without the need of a scan platform.

CREATING IMAGES WITHOUT POINTING THE CAMERA

JPL demonstrated a new concept to support imaging instruments (e.g., imaging lidars, imaging radars, hyper-spectral imagers) that could potentially eliminate the need for scanning optics or pointing systems in small spacecraft. Eliminating the need for orientation control or an optical scan platform for modern NASA instruments to construct images would greatly reduce the payload requirements of motors, actuators or thrusters, and associated fuel. This would enable an instrument to be carried on much smaller platforms like CubeSats.

The concept leverages advances in commercial, low-cost CMOS inertial measurement units (IMUs) developed for gaming platforms that can track their orientation with sub-milliradian drifts over several hours.

The CMOS IMU, a combination of accelerometer and gyroscope, tracks the acceleration/orientation of the spacecraft or instrument at all moments in time during an encounter or event. The data captured from an instrument is synchronized with this orientation tracking and both sets of data are used to indirectly reconstruct an image by back-calculating the position the instrument was in when the data was collected.

In this fashion, the entire 3D geometry of the surrounding area can be reconstructed with post-processing using several vector calculus transforms.

JPL's technology demonstration coupled a low-cost CMOS LIDAR system to measure range with a CMOS IMU to measure orientation.

Potential applications include dropping small spacecraft with basically any instrument in JPL's sensing portfolio into craters or caverns on low gravity asteroids, comets, or even the lunar surface to image environments inaccessible or too risky for a large spacecraft to navigate. Small CubeSats could image their environment as they "free fall" through space. The next step would be to deploy a coordinated swarm of these low-cost sensors to provide a robust imaging solution.

This technology can help NASA get "eyes" on currently inaccessible and high-risk areas with low cost, high return spacecraft. On Earth, this technology could enable a handheld, mm-wave sensor body-scanner about the size of a flashlight to replace the current, expensive TSA portals we stand in at airports to inspect bags and passengers.

This technology can help NASA get "**EYES**" on currently inaccessible and high-risk areas with low cost, high return spacecraft.

A LARGER, LASER SHARP PIPELINE OF DATA

Information can never travel faster than the speed of light — Einstein was right about that. But through optical communications research, we can increase the amount of information we send back from space.

JPL is developing NASA's Deep Space Optical Communication (DSOC) project to meet the ever increasing demand for returning larger volumes of data from space. DSOC aims to perform the first proof-of-concept demonstration of bidirectional optical communication from deep space. Optical communication systems can offer 10–100x the data rates compared to state-of-the-art radio links from deep space, using the same mass and power on the spacecraft. This can enable more sophisticated, data-intensive instruments for planetary science and astrophysics, as well as support human space exploration of Mars.

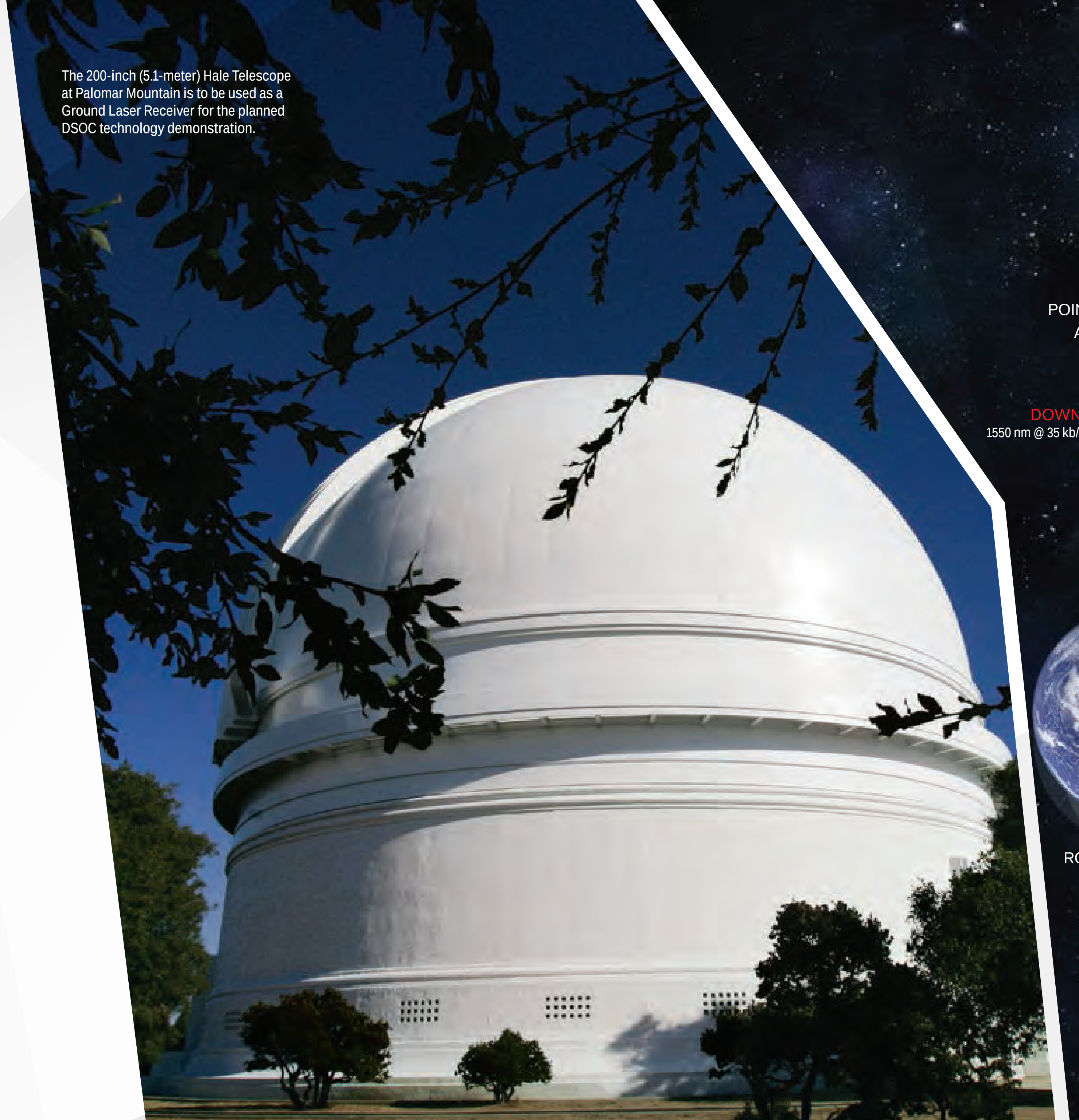
While optical communication systems from Earth orbit are well established, optical communication from deep space introduces entirely new challenges. JPL has been developing the core technologies to enable a DSOC technology demonstration mission. The architecture is based on transmitting a laser beacon from Earth to the spacecraft to assist the pointing back of the downlink laser beam. The distance causes huge losses of laser signal, requiring DSOC to have robust link acquisition and tracking to find the dim laser beam to enable error-free communications.

DSOC's key technologies are: photon-counting detectors to enable laser uplink from Earth to acquire and track the spacecraft, once the laser is acquired by the spacecraft; an active-passive vibration isolation platform to address the pointing challenges of aiming a laser at Earth from deep space; and finally, single photon-counting detectors on the ground that can be integrated with large aperture diameter ground telescopes to detect the faint downlink signal from deep space.

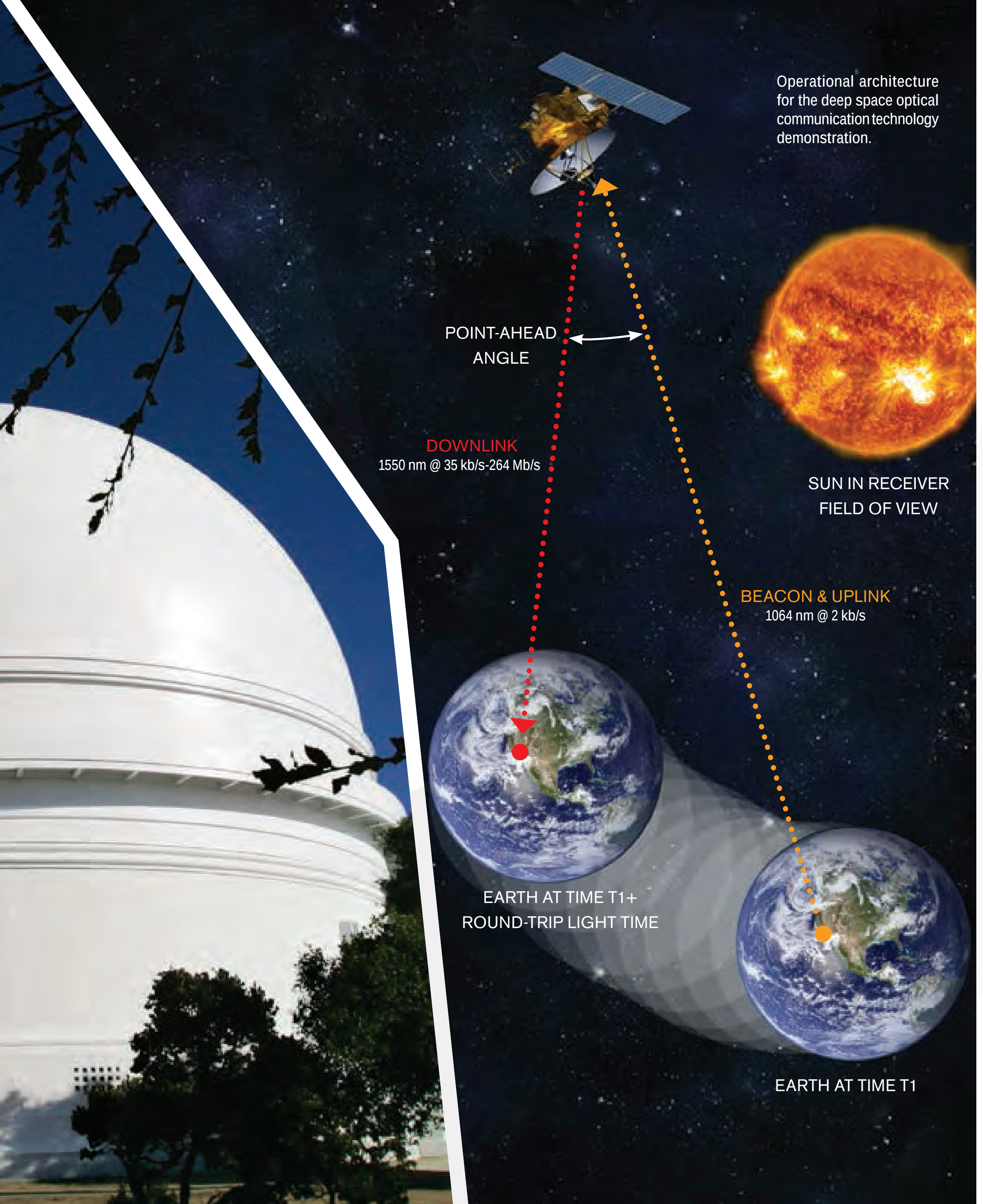
The JPL detectors were successfully demonstrated with NASA's Lunar Laser Communication Demonstration Project managed by NASA Goddard Space Flight Center and hosted by the Lunar Atmosphere Dust and Environment Explorer (LADEE) spacecraft, which orbited the Moon from October 2013 to April 2014. This technology demonstration, with components on LADEE and on the ground, downlinked data encoded in laser pulses, and made use of ground receivers based on single photon counting detectors.

The DSOC project is managed and implemented entirely at JPL and will be part of the next Discovery mission scheduled to launch in 2021. Its ground receiver terminal will use the 200-inch Hale telescope at the Palomar Observatory and its ground uplink terminal will use the Optical Communication Telescope Laboratory at JPL's Table Mountain Observatory.

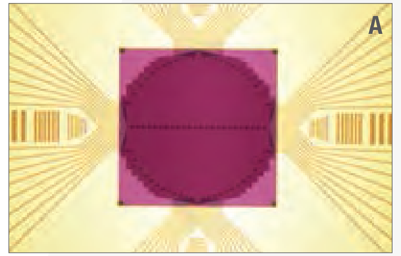
DSOC superconducting nanowire detectors were developed in collaboration with the National Institute of Standards and Technology.

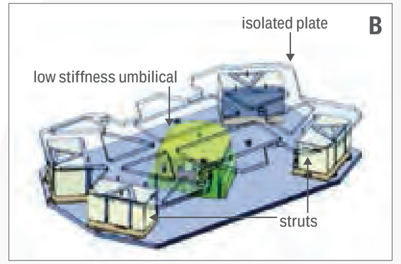


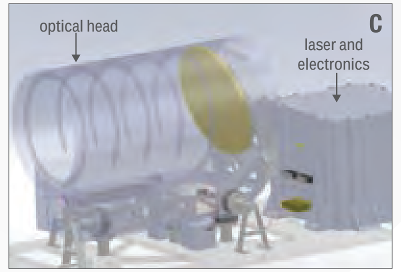
The 200-inch (5.1-meter) Hale Telescope at Palomar Mountain is to be used as a Ground Laser Receiver for the planned DSOC technology demonstration.

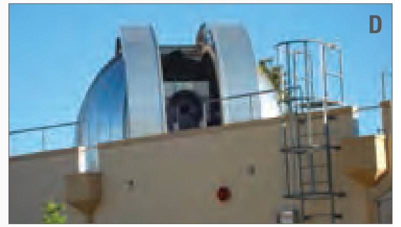


Operational architecture for the deep space optical communication technology demonstration.





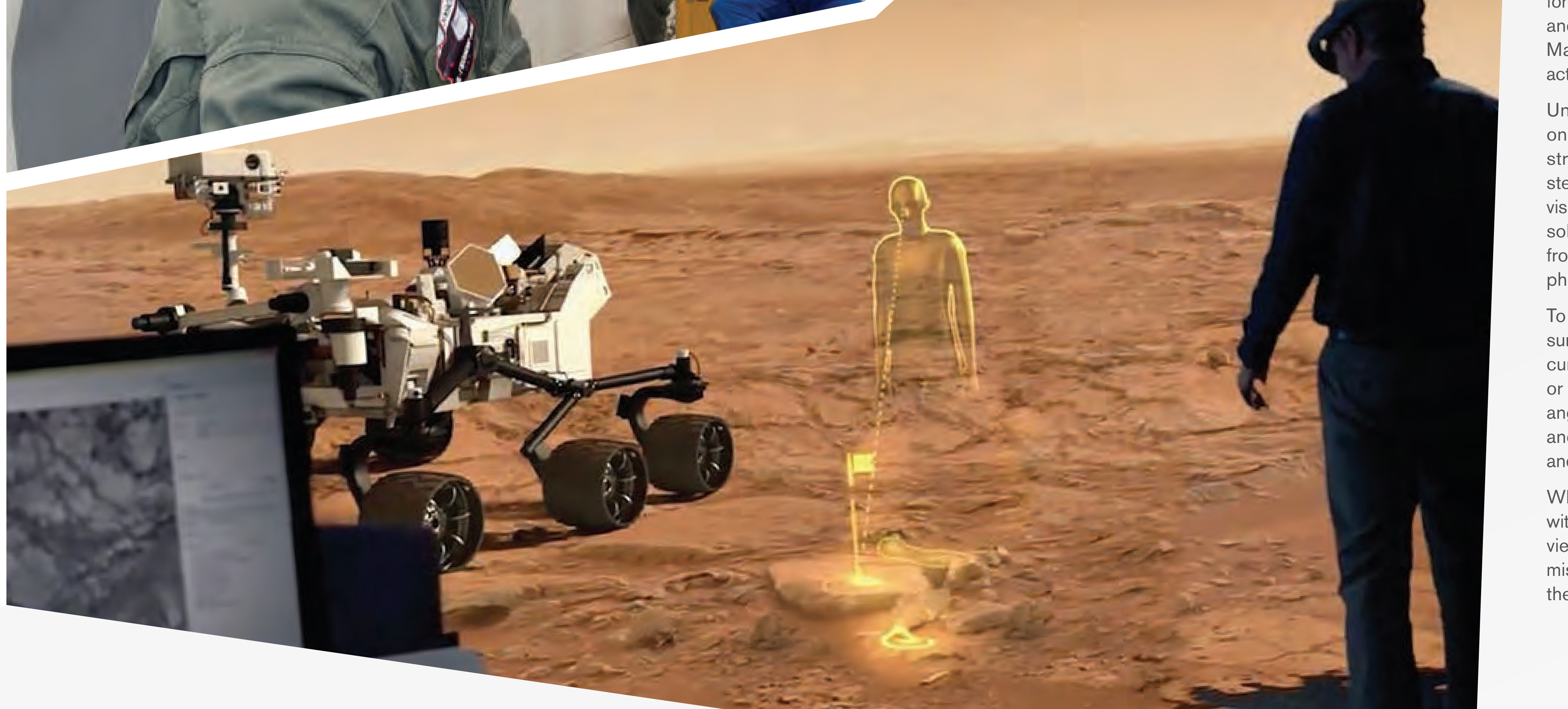




[A] Optical microscope image of a free-space-coupled 64-pixel SNSPD array for the DSOC ground receiver. **[B]** Solid model rendering of the Isolation Pointing Assembly (IPA). **[C]** The Deep Space Optical Communication (DSOC) Flight Laser Transceiver (FLT) conceptual solid model. **[D]** The OCTL 1m diameter telescope facility at JPL's Table Mountain Observatory.

[A-B] Screen views from OnSight, a software tool developed by NASA's Jet Propulsion Laboratory in collaboration with Microsoft. OnSight uses real Mars rover data to create 3-D simulations of the Martian environment where mission scientists can "meet" to discuss rover operations and do science planning. The tool provides access to scientists and engineers looking to interact with Mars in a more natural, human way. **[C]** Astronaut Scott Kelly used Sidekick to make the first Skype call from space. By connecting astronauts to experts on the ground, mixed reality could be transformational for scientific and engineering efforts in space.

JPL's Jeff Norris and Microsoft engineers test Project Sidekick on NASA's Weightless Wonder C9 jet.



TICKET TO ANYWHERE: MIXED REALITY FOR EXPLORATION

JPL's Ops Lab has been innovating a variety of immersive software applications using the Microsoft HoloLens mixed-reality headset. "Mixed reality" means that virtual elements are merged with the user's actual environment, creating a world in which real and virtual objects can interact. JPL-affiliated HoloLens applications furthered the work of a pilot user group of scientists and engineers at JPL in 2015.

The OnSight software, initially developed by JPL in collaboration with Microsoft, renders a 3D environment for Mars exploration. OnSight transports mission scientists and engineers from their offices to a virtual version of the Martian surface where they can collaborate, plan new activities for the rover, and identify potential science targets.

Until now, operators have had to analyze rover images on a screen and make inferences about the shape and structure of geologic formations. But images, even 3D stereo views, lack the natural sense of depth that human vision employs to understand spatial relationships. OnSight solves this problem by fusing together the latest datasets from orbital and surface instruments to produce a unified photo-realistic model of Mars.

To view this model, users don a HoloLens device and are surrounded by a holographic overlay of Mars at Curiosity's current location. They can stroll around the sandy surface or crouch down to examine rocky outcrops from different angles. By rendering imagery from the user's perspective and at the user's scale, the tool provides a more natural and intuitive mechanism for interacting with the red planet.

While "on Mars," users can collaborate and communicate with one another via an avatar that mimics their location and view direction. Because OnSight integrates with current mission planning tools, users can create a new target for the rover using natural gestures.

OnSight met a number of important milestones in 2015 including initial deployment into mission operations for the Curiosity rover and the end-to-end automation of its terrain processing pipeline. Mars Science Laboratory science team members recently used OnSight to help identify the transition point between two Martian rock formations, and made recommendations about where the rover should drive to study the formations in greater detail. Since summer 2015, OnSight has been developed entirely at JPL. NASA's Kennedy Space Center will host a public version of OnSight called "Destination: Mars," co-developed by JPL and Microsoft, in summer 2016.

A separate HoloLens software application called Proto-Space was conceived of and developed at JPL. Engineers responsible for the design and assembly of spacecraft use ProtoSpace to get a sense of what a new spacecraft would look like using 3D models of its design. ProtoSpace allows the user to see and manipulate a full-scale hologram of a rover or other spacecraft before a single component has been built.

In December 2015, a HoloLens headset, loaded with a different JPL-managed application called Sidekick, was sent to the International Space Station. Astronaut Scott Kelly later used Sidekick to make a Skype call from space. JPL is now in the process of developing new concepts for the future use of Sidekick on the station.

The goal of the **PHYTIR** project was to mature key components of the HyspIRI radiometer.

The HyspIRI mission, endorsed by the National Research Council's Decadal Survey, would provide hyperspectral visible through short-wave-IR (VSWIR), and multi-spectral Thermal IR (TIR) imagery of Earth.

The TIR data would be used to monitor changes in temperature and composition of Earth's surface and use that information for answering critical science questions.

JPL's Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR) is a state-of-the art, multi-band thermal imager that meets the form, fit, and functional requirements for HyspIRI's TIR. The goal of the PHyTIR project was to mature key components of the HyspIRI radiometer and reduce the risk and cost of the HyspIRI mission implementation by developing an instrument prototype and testing it in a space-relevant environment.

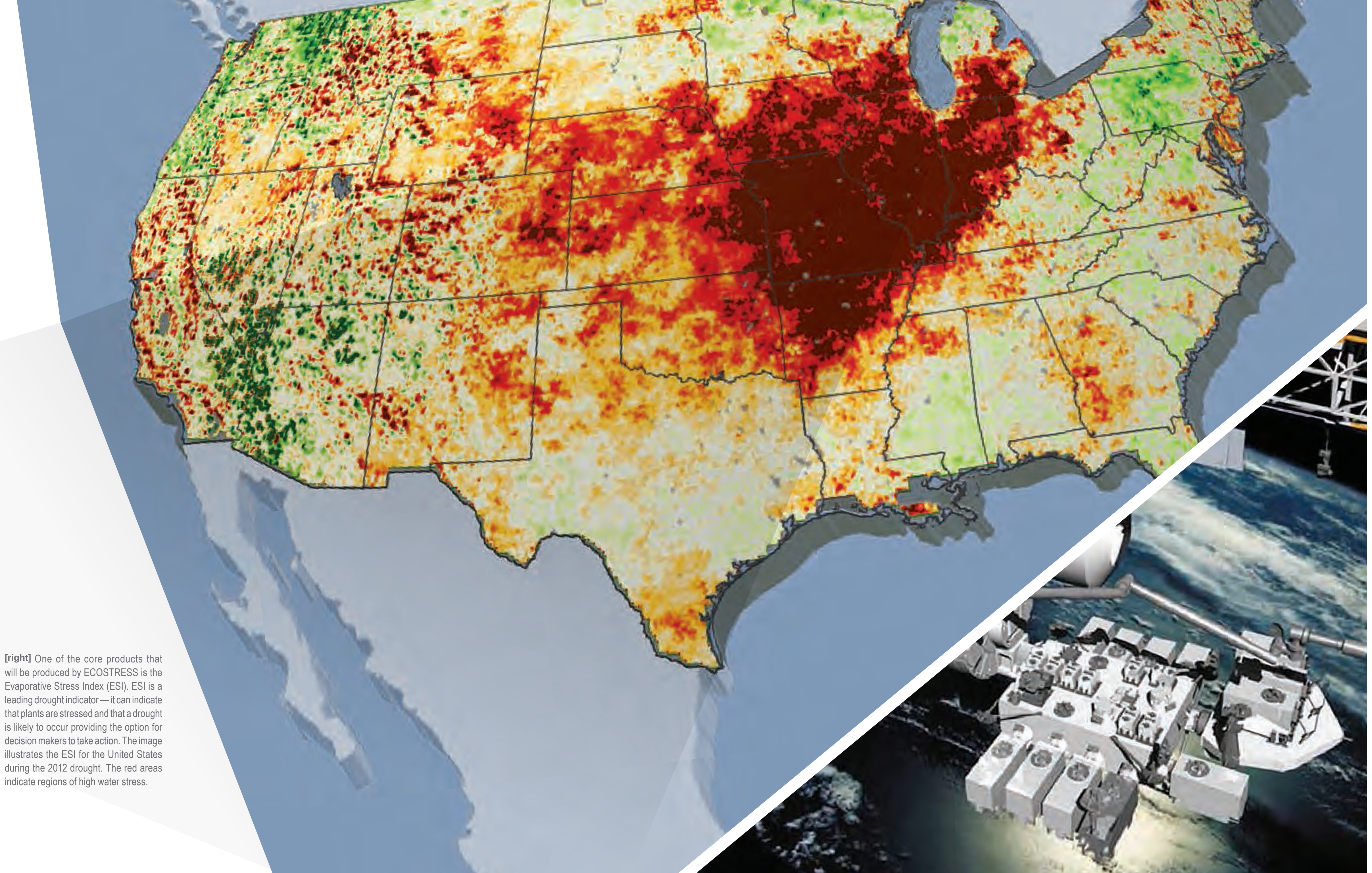
A key success of the PHyTIR project was demonstrating that the detector design met mission imagery requirements and that the scanning and pointing systems met pointing knowledge requirements.

JPL developed the instrument concept and design, and partnered with Teledyne to produce the detector arrays. JPL designed all the optical and mechanical components and assembled and tested the system.

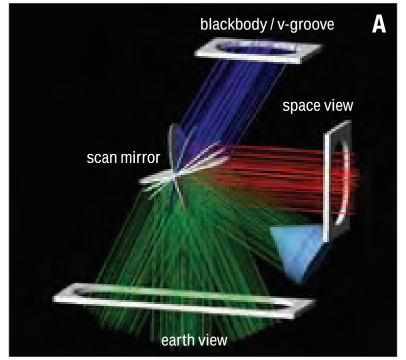
PHyTIR was selected by NASA's Earth Venture Program as the instrument for the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS). ECOSTRESS will provide critical insights into plant water dynamics and how ecosystems change with climate via high spatiotemporal resolution thermal infrared radiometer measurements of evapotranspiration (ET). ECOSTRESS is scheduled to be deployed on the International Space Station (ISS) in 2018.

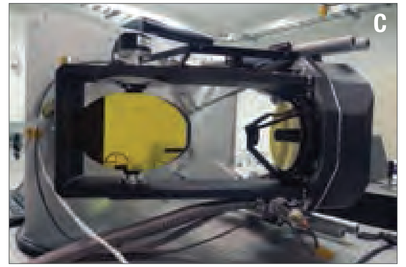
This technology was developed in partnership with University of Idaho, Moscow, US Department of Agriculture, Princeton University; and University of Maryland, College Park.

REDUCING **RISK** AND STUDYING **STRESS**



[right] One of the core products that will be produced by ECOSTRESS is the Evaporative Stress Index (ESI). ESI is a leading drought indicator — it can indicate that plants are stressed and that a drought is likely to occur providing the option for decision makers to take action. The image illustrates the ESI for the United States during the 2012 drought. The red areas indicate regions of high water stress.

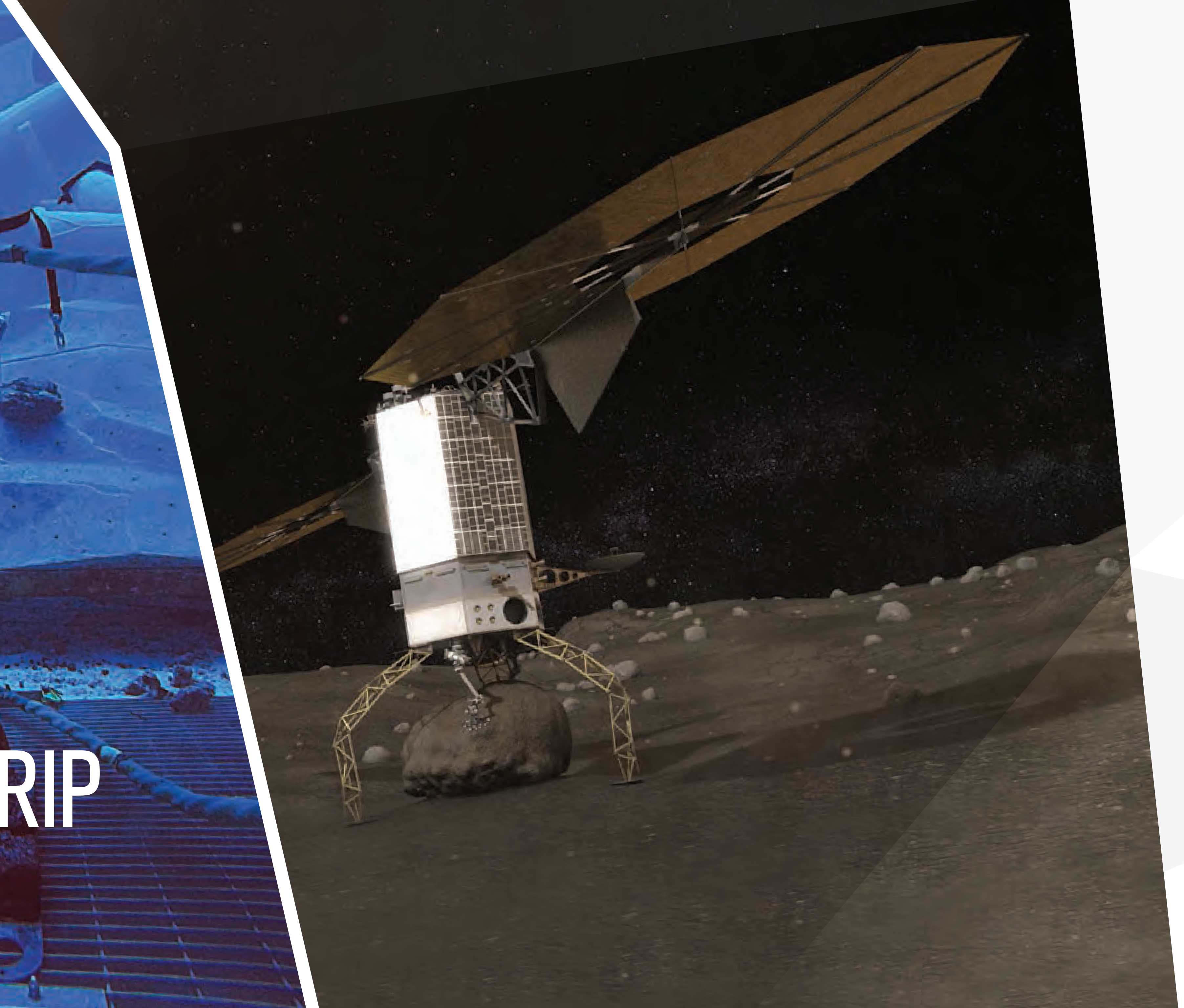




[A] HyspIRI ray trace showing various views allowed by the scan mirror. The space and blackbody views allow the instrument to be radiometrically calibrated which ensures the data captured in the Earth view is scientifically useable. **[B]** Solid model rendering of Prototype HyspIRI Thermal Infrared Radiometer as designed to interface with the International Space Station's Japanese Experiment Module. **[C]** PHyTIR scan head mounted in the laboratory during testing gold coatings are applied to the mirrors to allow maximum reflection of infrared light. **[left]** Artist rendering showing where the ECOSTRESS radiometer will be deployed on International Space Station (ISS) on the Japanese Experiment Module—External Facility (JEM-EF).

KEEPING A FIRM GRIP ON SCIENCE

An "aquanaut" in the NEEMO 20 mission that simulated an EVA at Phobos, tests the microspine gripper's abilities in a low gravity environment.



Microspine grippers, developed at JPL, enable mobility on natural rock in any orientation in any gravitational field. These devices features toe-like appendages called "carriages" that each contain dozens of steel hooks. When the gripper connects with a rocky surface, these hooks cling to the rough terrain. The carriages then simultaneously pull themselves toward the center of the gripper.

These microspine-based anchors are being developed at JPL for gripping rocks on the surfaces of comets and asteroids. They could also be used on cliff faces and lava tubes on both Earth and Mars. A robot designed for exploring low-gravity rugged terrain would have these grippers on its feet, allowing it to climb around without falling off or drifting away.

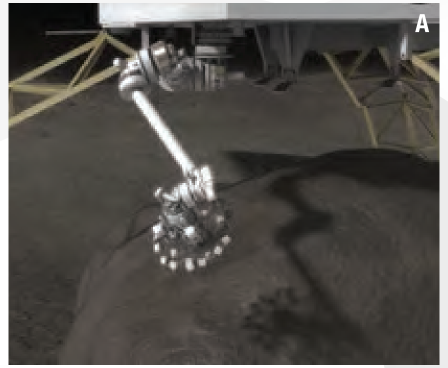
Two microspine grippers were tested by the NASA Extreme Environment Mission Operations (NEEMO) project in 2015. NEEMO, located in the Florida Keys National Marine Sanctuary, sends groups of astronauts, engineers and scientists to live in its Aquarius Reef Base undersea research station for up to three weeks, providing an excellent analog to space exploration habitats. The NEEMO 20 mission is a simulation of a crewed mission to the surface of Phobos, a moon of Mars. For NEEMO 20, the hand-operated microspine grippers were designed to provide aquanauts with an alternative method for stabilizing both themselves and a payload.

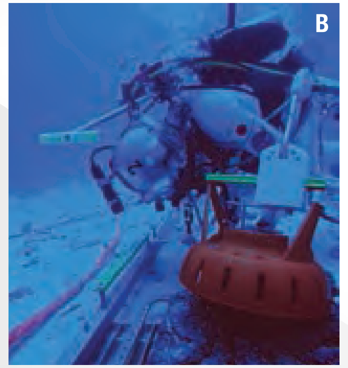
Aquanauts performed four simulated asteroid extra-vehicular activities (EVAs) in which they used the microspine grippers. They were able to obtain both a soil and surface sample, while attached to only the microspine grippers and a safety tether. They also used the grippers to anchor and deploy a large payload the next day.

JPL will use these test results to further improve the microspine technology for future missions. The technology was selected as a candidate for the planned Asteroid Redirect Mission (ARM).

In July 2015, aquanauts performed two simulated asteroid extra-vehicular activities **(EVAS)** each day, in which they used the microspine grippers.

[left] Artists concept of NASA's proposed Asteroid Redirect Robotic Mission capturing an asteroid boulder before redirecting it to an astronaut-accessible orbit around Earth's moon. **[A]** Artistic rendering of the selected Asteroid Redirect Mission concept which will include two microspine gripper tools. **[B]**"Aquanaut" at the NEEMO 20 mission in Key West, Florida is stabilized by a deployed microspine anchor.





SUPERCHARGING SPACE COMMUNICATION

Ever wonder why stars twinkle? This effect is caused by variations in the density of our atmosphere that cause blurring in light coming from space. It's pretty for stargazing, but a challenge for space-to-ground communications.

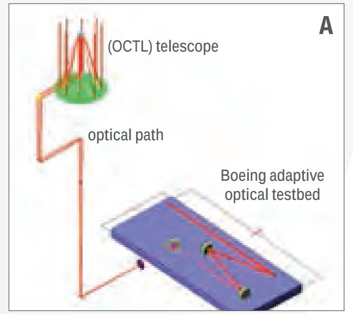
A key technology called "adaptive optics" corrects such distortions. By combining the adaptive optics instrument, provided by Boeing, with JPL's laser communications technology aboard the International Space Station (ISS), JPL is working toward advances in space communications that could have major benefits for our data transmission needs here on Earth as well.

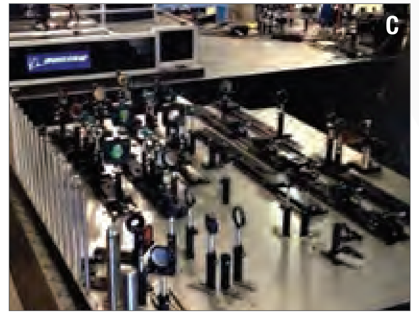
JPL's Optical Payload for Lasercomm Science (OPALS) has been conducting cutting-edge research on data transmission since it successfully beamed high-definition video via laser from the ISS in June 2014. That transmission beamed packets of data in 3.5 seconds versus the 11 minutes it would have taken using traditional radio waves.

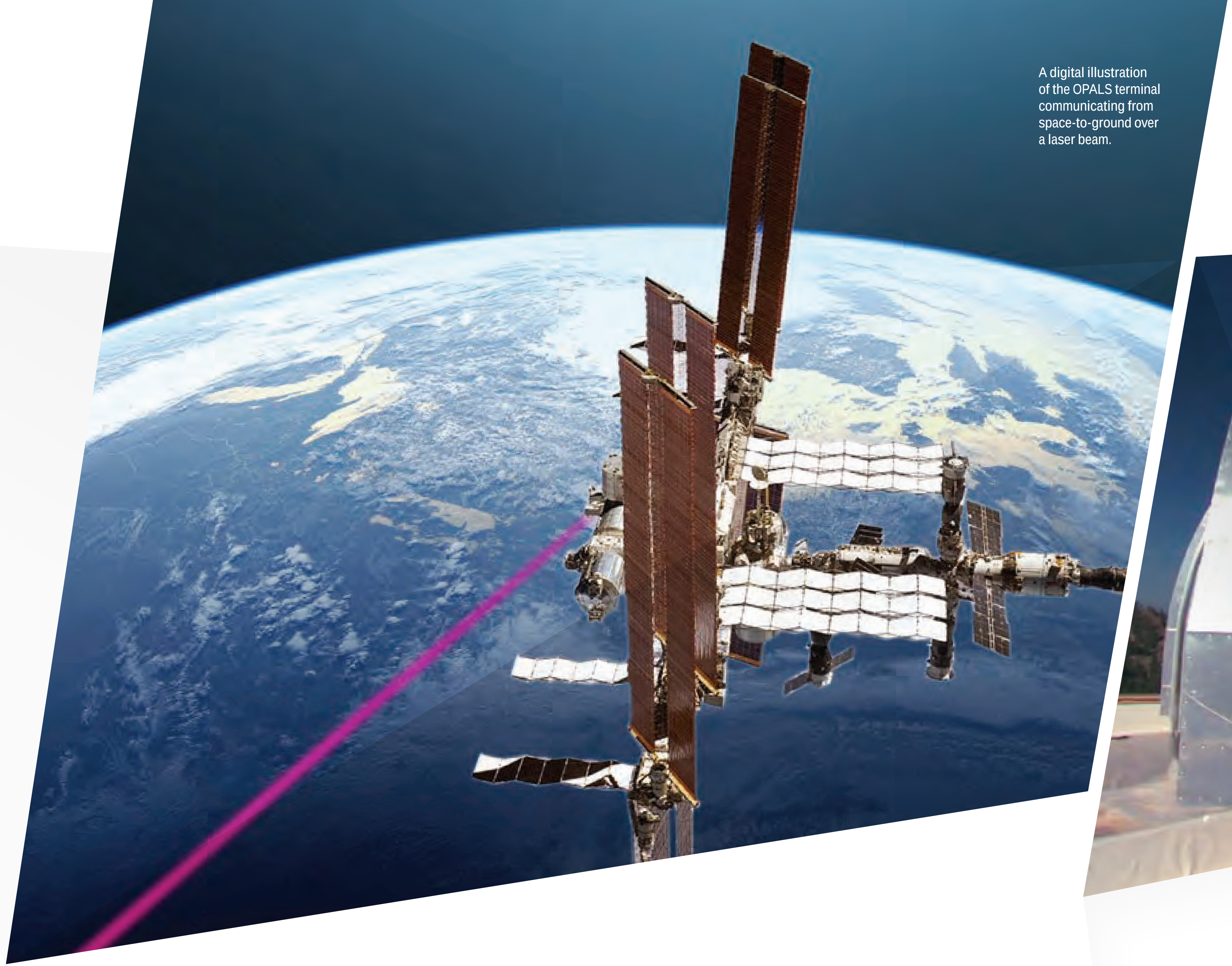
In March 2015, OPALS demonstrated that the laser signal from the ISS can be focused into single-mode optical fibers on the ground, the standard in the telecommunications industry. The March demonstration advances the science of spacecraft-to-ground high-rate data transfer, potentially supporting links of tens of gigabits per second. This first demonstration of continuous adaptive optics correction lays the path for future robust, high-rate optical communications between low Earth-orbit and the ground.

For commercial ventures, this can mean higher definition video feeds from near-Earth assets, such as satellites, improving the interaction and experience with the stakeholders, whether they are researchers, engineers, or consumers.

NASA Johnson Space Center accommodated the OPALS payload on ISS.



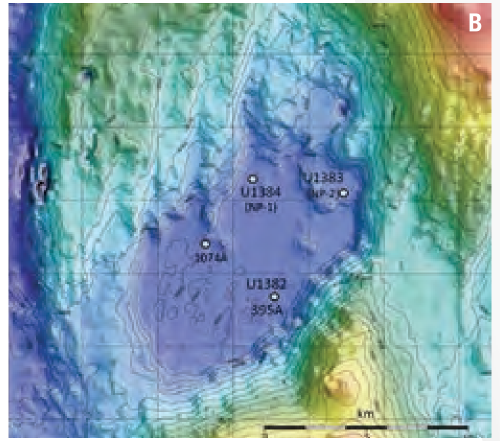


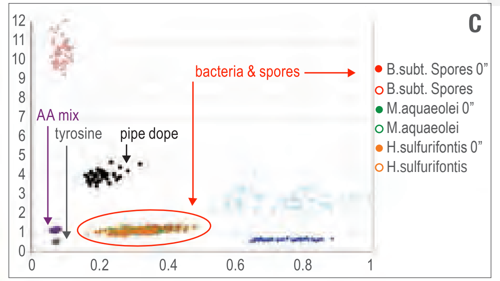


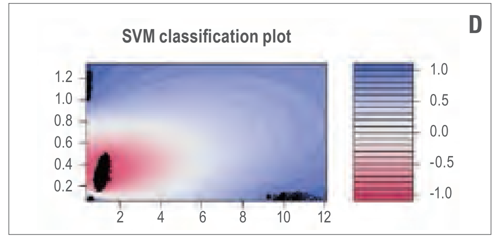
A digital illustration of the OPALS terminal communicating from space-to-ground over a laser beam.

JPL's Optical Payload for Lasercomm Science (OPALS) has been conducting cutting-edge research on data transmission since it successfully beamed high-definition video via laser from the ISS in June 2014.

[above] The NASA/JPL Optical Communication Telescope Laboratory (OCTL) located at the Table Mountain Observatory near Wrightwood, California was used as the ground station for the OPALS demonstration. **[A]** OPALS ground receiver optical path to the OCTL Coudé room optical bench. **[B]** Close up image of OCTL. **[C]** The Boeing Adaptive Optical Testbed retrofitted to the OPALS ground receiver at the OCTL Coudé room optical bench.







Deep Exploration Biosphere Investigative tool team deploying DEBI-t into a borehole 0.5 km below ocean floor for in-situ microbial analysis.

UNDERSTANDING DEEP LIFE ON EARTH

The Earth's deep biosphere is a major frontier for science. Recent studies have shown the presence and activity of cells in deep marine sediments and in the continental deep biosphere. Understanding the distribution of deep life in the subsurface biosphere is a major challenge to advancing our understanding of the evolution life and ecosystems on Earth.

A team of researchers from JPL, Photon Systems Inc., the University of Leicester (UK), Lamont-Doherty Earth Observatory, and the University of Southern California (USC) developed and applied a novel technology method, the Deep Exploration Biosphere Investigative tool (DEBI-t), a novel in situ logging tool designed to detect microbial life harbored in a deep, native, borehole environment within igneous oceanic crust, using deep ultraviolet native fluorescence spectroscopy.

To date, all methods developed to detect microbial life in the deep biosphere involve in-lab analysis of recovered materials from boreholes. Materials are analyzed for microbial biomass by extracting cells or cellular components, or by application of dyes to samples and performing cell counts. These current methods are highly laborious and inefficient, involving both cell loss and the loss of information about the mineralogical context that may have an influence on the microbial ecology.

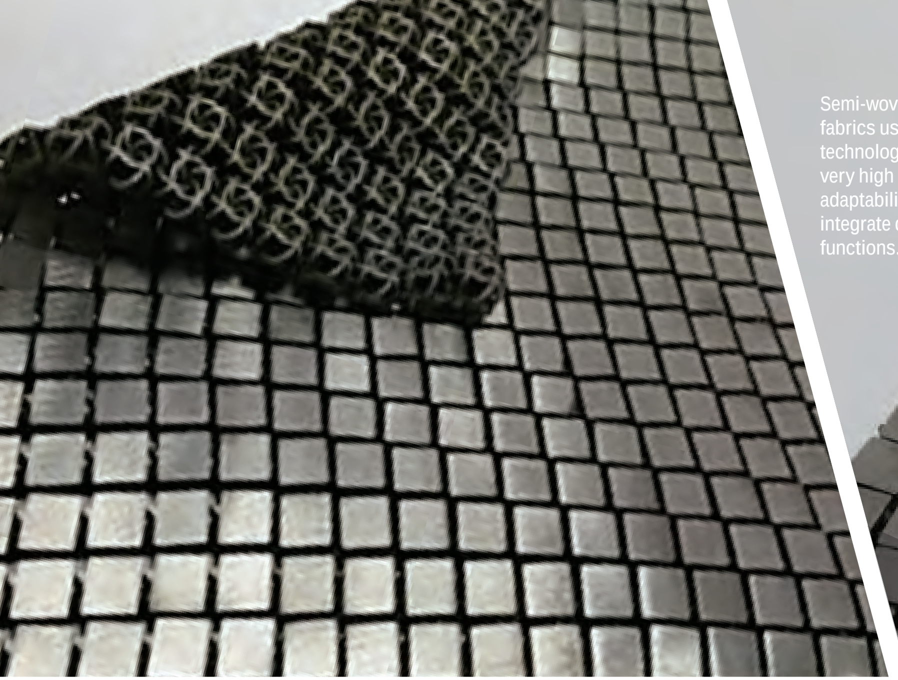
DEBI-t was deployed in Hole 395A, a Deep Sea Drilling Program legacy borehole, located at the North Pond site in the western flank of the Mid-Atlantic Ridge. The instrument acquired native fluorescence data during two complete passes of the borehole, where logs were obtained in both the downhole and uphole directions. Embedded control software directed the instrument to fire the laser, collect data, and transmit information uphole when power was supplied.

The detected bioload within Hole 395A is, to the best of the team's knowledge, the first set of microbial data collected in situ and in real-time.

Leveraging the DEBI-t effort, JPL is leading the development of instruments for detection of potential biosignatures on Mars with SHERLOC (Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals) on the Mars 2020 rover, as well as a new ice drilling and in-situ biomass detector in subsurface ice in Greenland as a testbed for future Europa subsurface missions.

[A] Researcher initializes DEBI-t's autonomous on-board software for data logging. **[B]** Bathymetric map showing the location of Borehole 395A in the North Pond at the Mid-Atlantic Ridge. **[C]** Representation of the spectral library used to train the classification algorithm to determine microbial signatures from background. **[D]** Contour plot constructed using a classification algorithm (Support Vector Machine) was used to determine microbial signatures in Hole 395A.

DEBI-t was deployed in Hole 395A... in the western flank of the Mid-Atlantic Ridge. To the best of the team's knowledge, it represents the first set of microbial data collected in situ and in real-time.



Semi-woven 3-D printed fabrics using DLMS technology present a very high geometrical adaptability while they integrate different functions.

[left] Researcher Raul Polit Casillas measuring the final dimensions of 3D printed fabric in stainless steel. **[upper left]** Different finishing on both sides of the multifunctional fabric showing difference in reflectivity. **[lower left]** Checking the metal textile sample as it comes from the 3D printer after some basic post processing.

A STITCH IN TIME AND SPACE

3D-printed woven textiles represent a potential new frontier in designing adaptable and multi-functional spacecraft structures whose shapes need to be altered, such as large foldable antennas and reflectors. Researchers at JPL are developing such fabrics with the goal of being able to someday manufacture them in space. Through innovating unique geometries that endow the fabrics with a variety of functions, JPL is paving the way in the domain of printing 4D designs.

The prototypes designed by JPL researchers look like chain mail, with small silver squares strung together. But these fabrics were not sewn by hand. Instead, they were made through additive manufacturing, in which material is deposited in layers to build up the desired object. Specifically, they used direct laser metal sintering or DLMS. This leads to an overall reduction in the steps required to manufacture such fabrics, and the ability to create unique architectures using these materials. Researchers 3D-printed and tested fabrics made of stainless steel. They also printed two other prototypes: one made of carbon-fiber reinforced nylon, and another in which that material was coated with chrome.

In generating these prototypes, advanced design techniques were used to create novel geometries for the fabrics. These design techniques are used for additive manufacturing to create fabrics capable of performing multiple functions simultaneously. The combination of geometries as well as material properties allows researchers to "print" functions into the fabrics, making them "4D-printed structures."

Additionally, different strategies for printing these fabrics have been implemented and tested, with an eye toward eventually manufacturing them in space. These strategies include making metal 3D-printed fabrics using a high-energy process, as well as using a lower-energy manufacturing process to create metal-plated composite fabrics.

These prototype multifunctional fabrics combine four essential functions within their geometries: reflectivity, passive thermal management, foldability, and tensile strength. For reflectivity, one side can reflect light based on its material finishing and geometry, while the other side is much less reflective. This is also a means of thermal control. It is designed with a much larger surface area, which dissipates more heat relative to the opposite side. The prototype fabrics can also be folded in many different ways and adapt to shapes while still being able to sustain the force of pulling on it. With functions derived from the behavior of their component materials and geometries, engineers consider these types of fabrics "4D-printed structures."

These fabrics could be especially useful for deployable devices because the material is highly foldable and compactable, and its shape can change quickly. They could also be adapted as meteorite shielding of a spacecraft, for astronaut EVA suits, for a mechanism of capturing objects on the surface of a planetary body, and other potential space applications. The fabrics could also be applied to non-NASA purposes, such as shielding, protective clothing, shading, building facades and wheel traction improvement in harsh terrains. A U.S. Temporary patent has been issued for this technology.

... acquire and encapsulate the **SAMPLE** in a single, quick sampling action. This capability is achieved with only one actuator and two activating bolts.

SNATCH AND RETURN A COMET SAMPLE

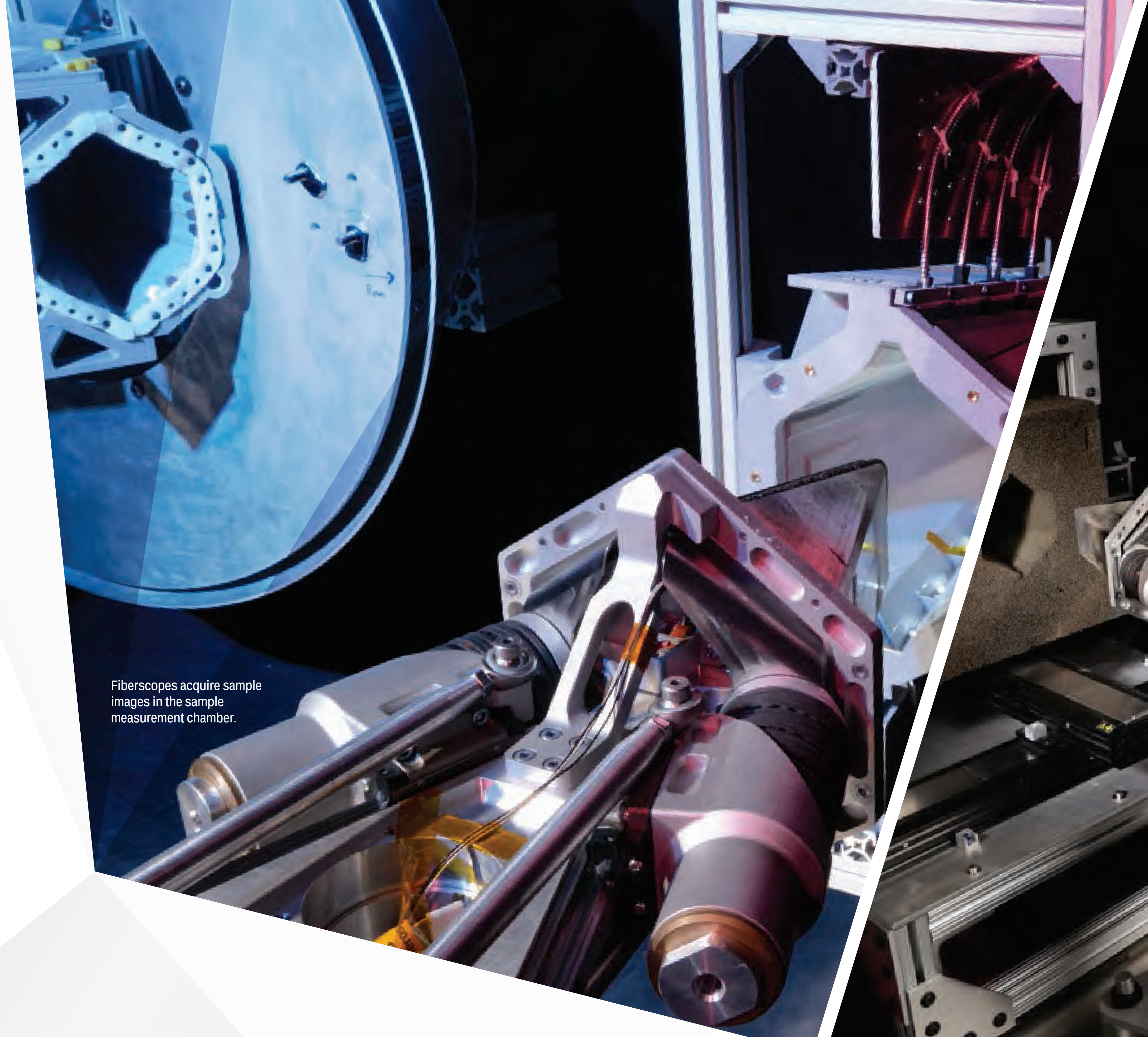
BiBlade is an innovative sampling tool developed and validated at JPL for a future sample-return mission to a small body surface such as a comet. The sampling tool has two blades that could be driven into the small body's surface to acquire and encapsulate the sample in a single, quick sampling action. This capability is achieved with only one actuator and two activating bolts, meeting the mission need of minimized tool complexity and risk.

BiBlade has several unique features that improve upon the state of the art—including the ability to acquire a sample to a depth of 10 cm and the ability to return two separate samples with one tool. These features also enable multiple sample attempts per sample, direct sample measurement, and the ability to perform fast sampling.

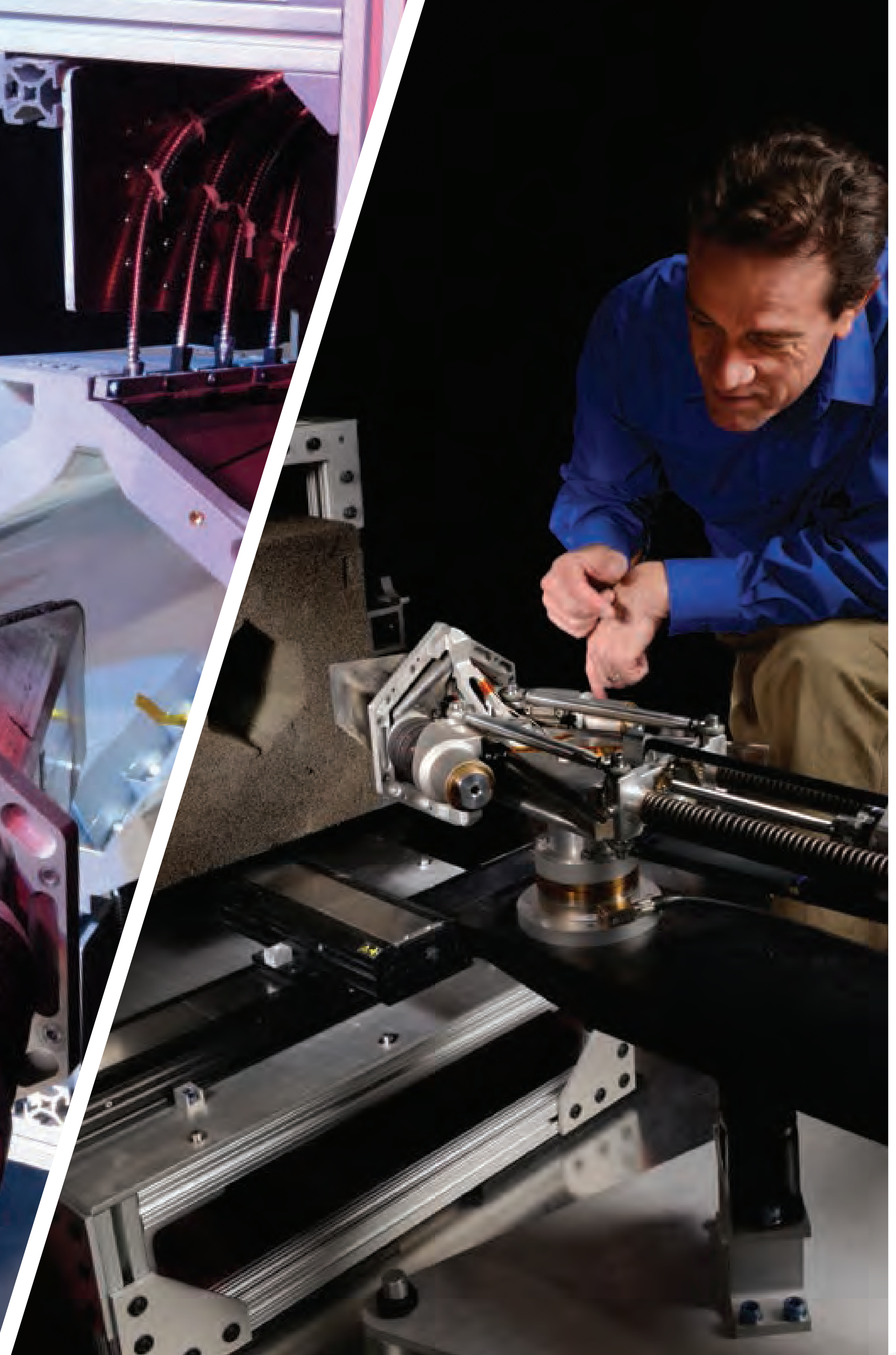
Two blades would be driven into the surface using springs, with the sampling action completed in about 30 milliseconds, and the spacecraft would thrust away from the comet immediately upon initiation of the sampling action. The robotic arm would transfer the sampler to a sample measurement station where the sample volume would be measured using a multi-fiberscope sample imaging system and then the sample would be transferred to a sample chamber in a Sample Return Capsule.

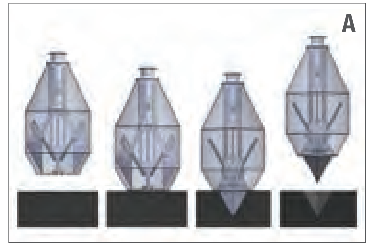
The robotic arm would be configured such that reacted forces during sampling would react through the spacecraft center of mass so sampling forces push the spacecraft away from the comet during the sampling event.

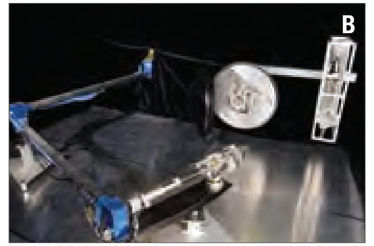
A prototype of the tool has been experimentally validated through the complete sampling chain using an innovative suite of simulants developed at JPL to represent the mechanical properties of a comet.

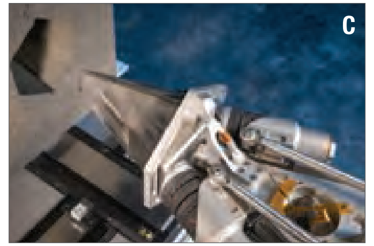


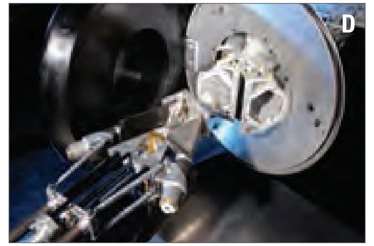
Fiberscopes acquire sample images in the sample measurement chamber.





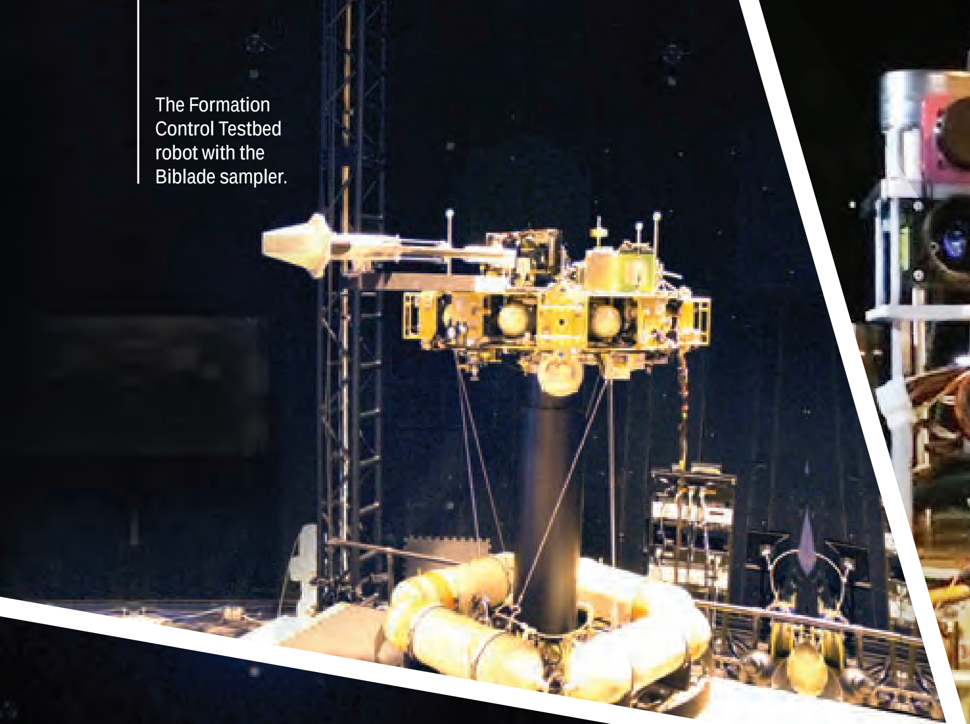


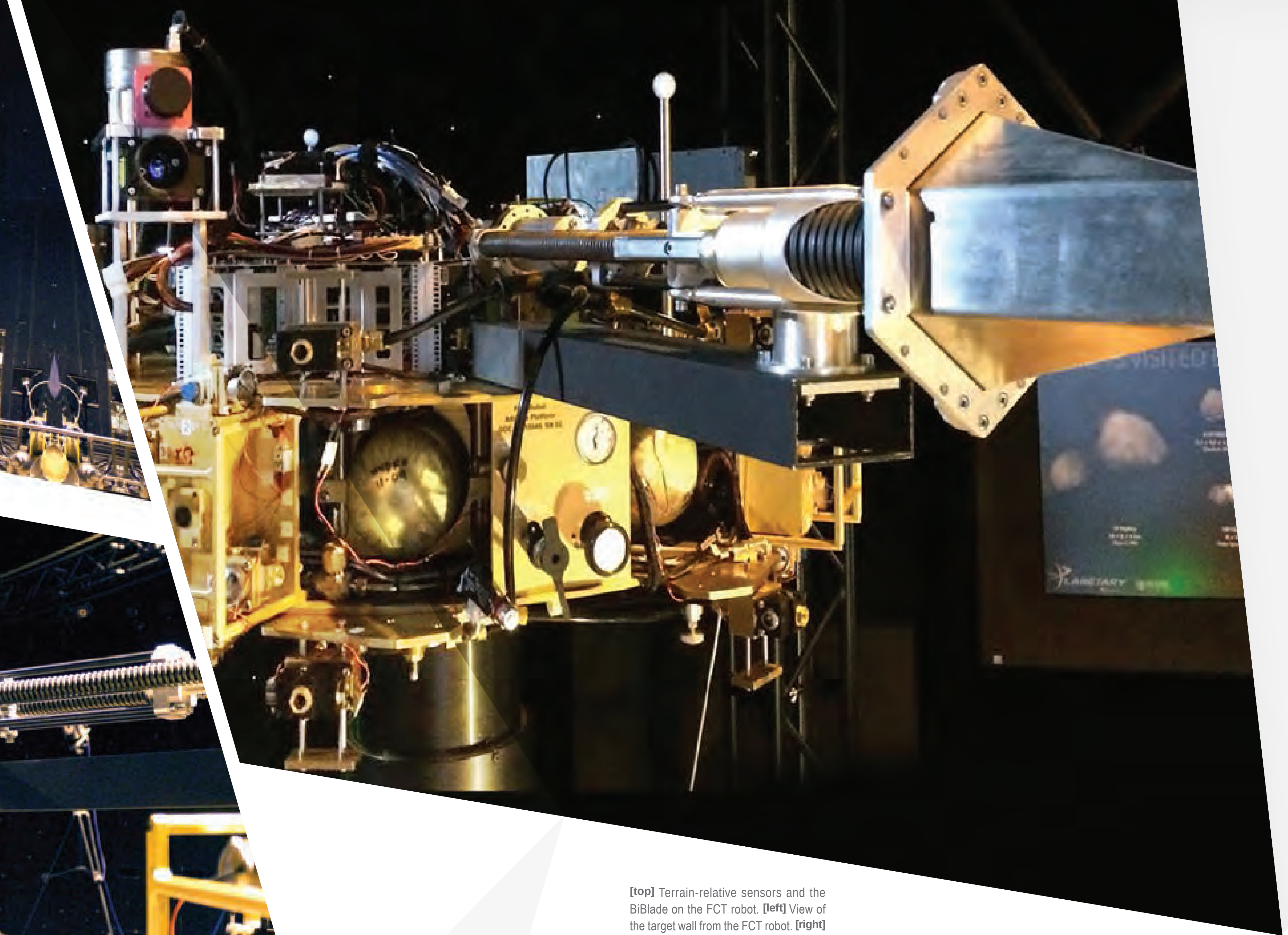


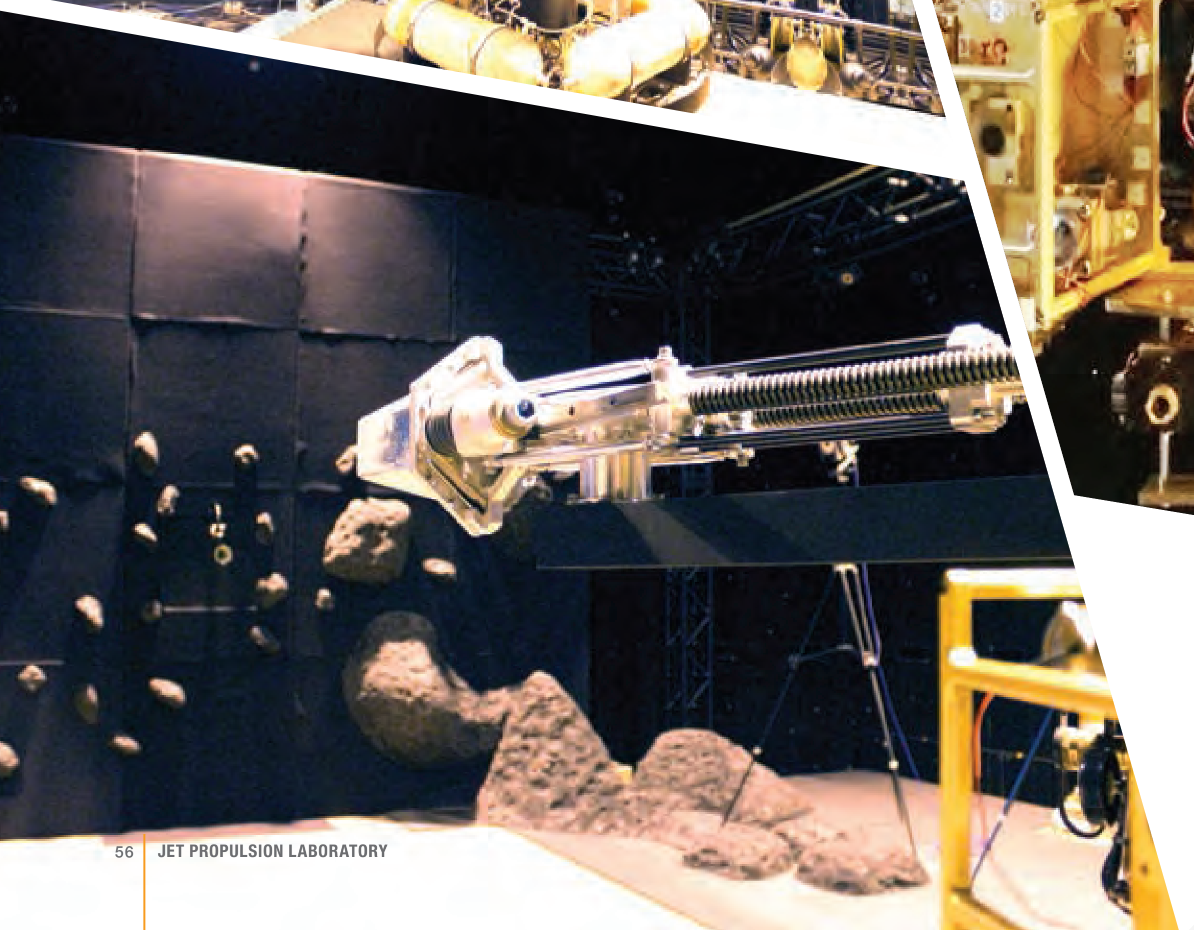


[A] Sampling process: approach, contact, sample, retract [right to left]. **[B]** Sampling chain testbed. **[C]** A void is left in the simulant where the sample was acquired. **[D]** A lid retains the sample in a Sample Return Capsule chamber. **[left]** Principal Investigator Paul Backes in the sampling chain testbed.

The Formation Control Testbed robot with the Biblade sampler.







CLOSE COMET PROXIMITY OPERATIONS ON EARTH

Operating and sampling in deep space with microgravity approximately 1/10,000th of Earth's gravity, with possible outgassing "geysers" of ice, and spacecraft communications that takes 30 minutes one way to Earth makes traditional human in the loop, or open control operations nearly impossible.

Using JPL's Formation Control Testbed (FCT), deep space environments can be emulated and the testbed can be used as a closed-loop, autonomous Sample Return Proximity Operations (ProxOps) testbed to emulate autonomous guidance, navigation, and control for sampling the surface of a comet. The FCT facility features two air-levitated, air-thruster-controlled robots, each with full, independent 6DOF motion with a full ground system for real-time telemetry and commanding. It allows testing with flight-like hardware and software on a platform that features the analogous dynamics to the zero gravity environment of space. The FCT is also currently being used to develop terrain-relative sensors and associated navigation and control algorithms and software used to estimate and control position and velocity to within various sampling tool dynamic requirements relative to the simulated surface of a sampling target.

A key advantage of the FCT is that it allows investigations into the true dynamics of a spacecraft under thruster control and its interaction with sampling/landing surfaces or docking with other bodies in space. In particular, it allows demonstration of capabilities for scenarios involving synchronized motion of a spacecraft with a non-collaborating object in space and the demonstration of system stability during comet sample acquisition while dealing with environmental uncertainties. It has been shown that with closed loop control, attitude and relative velocity requirements can be met to successfully sample a small body, and that autonomous detection of surface contact can be functionally provided by the ProxOps control system.

The "BiBlade" tool has also been developed and demonstrated at FCT as part of a closed-loop approach/sampling/departure scenario, following a profile that mimics in real-time the ProxOps sample return scenario. Results show that the comet surface contact can be measured by the control system, and that the proposed design to sample and react against the spacecraft does not result in loss of control of either spacecraft attitude or position.

[top] Terrain-relative sensors and the BiBlade on the FCT robot. **[left]** View of the target wall from the FCT robot. **[right]** Example of a computer vision sensor sequence approaching the target wall.

A key advantage of the **FCT** allows investigations into the true dynamics of a spacecraft under thruster control and its interaction with sampling/landing surfaces or docking with other bodies in space.

EYES IN THE RED PLANET'S SKIES

Getting around on Mars is tricky business. To have a better sense of where to go and what's worth studying on Mars, it would be useful to have a low-flying scout.

A team at JPL is developing a Mars helicopter, the latest in a line of ambitious, low-cost craft that would add a new dimension to exploring other worlds by taking to the air. A helicopter on Mars would work the same as a helicopter on Earth—the rotor blades spin up and produce lift because of the density of the atmosphere. One might think it's actually easier to fly one of these helicopters on Mars because its gravity is 3/8th of Earth's, but Mars' atmosphere is a hundred times less dense. Without that density, it has to spin even faster or get bigger rotor blades or get lighter. The Mars helicopter being developed will have rotors of 1.2 meters in diameter and have to spin at about 2600 rpm to provide lift to support its ultra-lightweight payload.

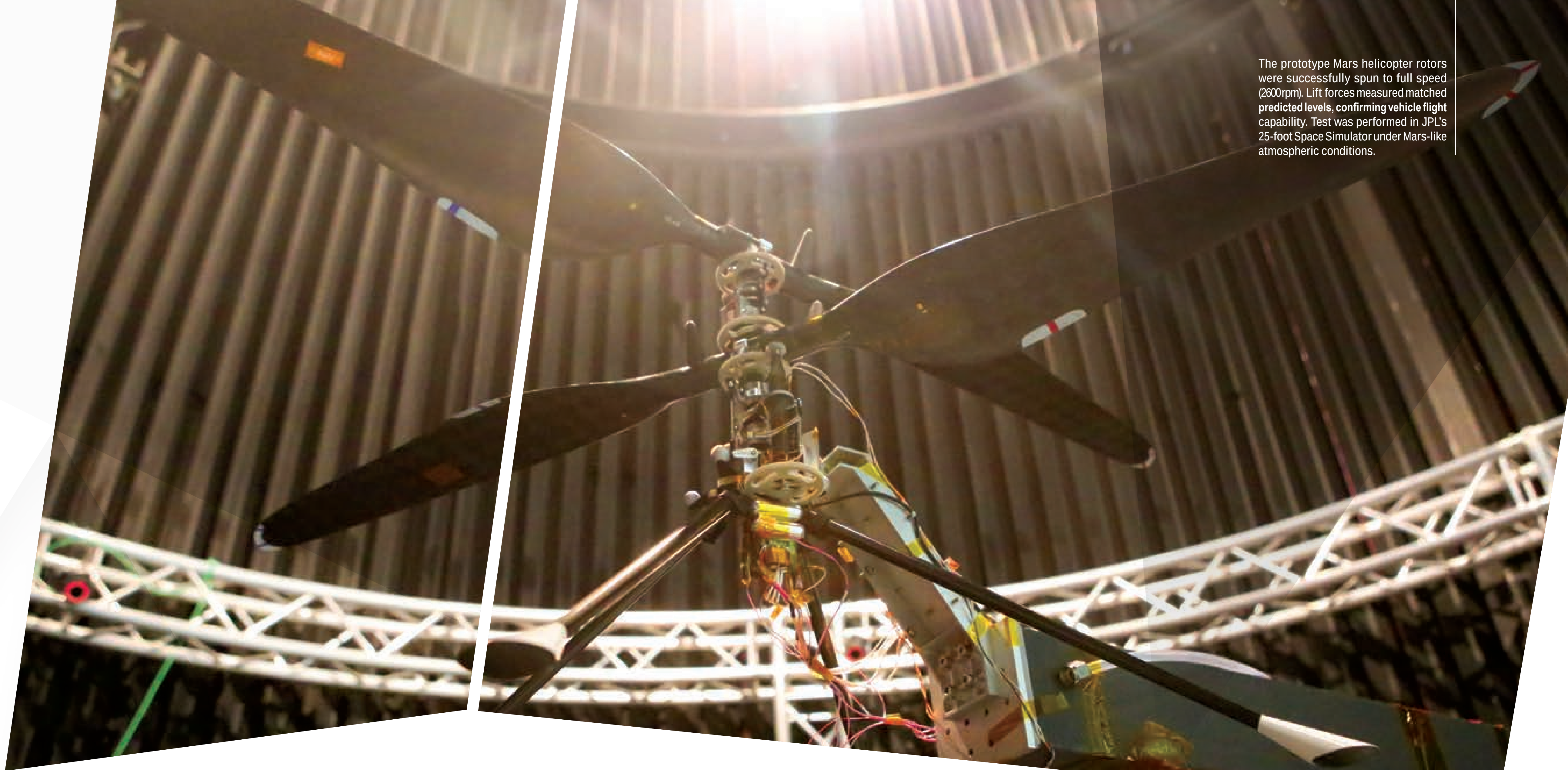
The autonomous, solar powered helicopter, envisioned to weigh about 3 pounds (1.4 kilogram), has a camera that would give NASA teams a heads up to what the rover might encounter ahead and steering it toward the best possible location, potentially tripling the distance that rovers currently drive in a Martian day.

After a few minutes of scouting out areas for near-future exploration, the autonomous craft would land on the surface to absorb solar energy via a top-mounted solar panel to recharge for the next day's activities.

The team even has a few ideas for the far-off future of the scout. Imagine a fleet of connected scouts surveying an area in great numbers, or the idea of adapting the technology to explore other worlds like Titan and Venus, and scaling up to carry other scientific payloads. But, for now, they have to get their prototype ready. As with all good scouts, they will be prepared for the next opportunity going to Mars.

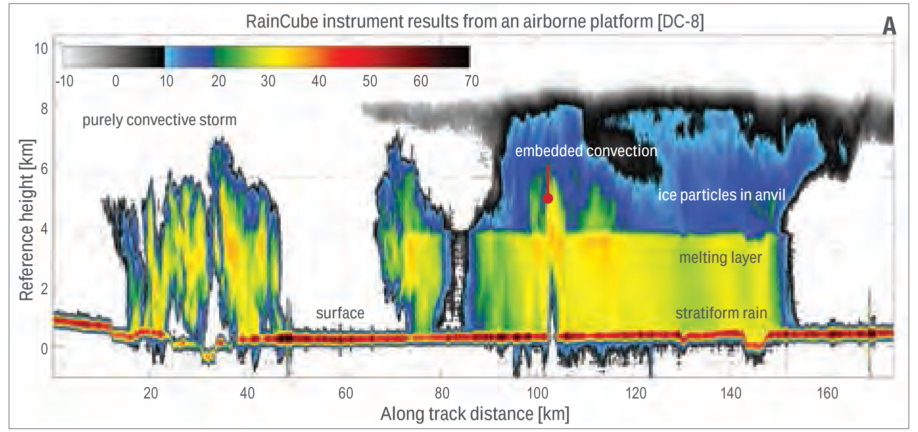
The Mars helicopter is under development in partnership with NASA Ames Research Center, NASA Langley Research Center, NASA Glenn Research Center, and AeroVironment, Inc.

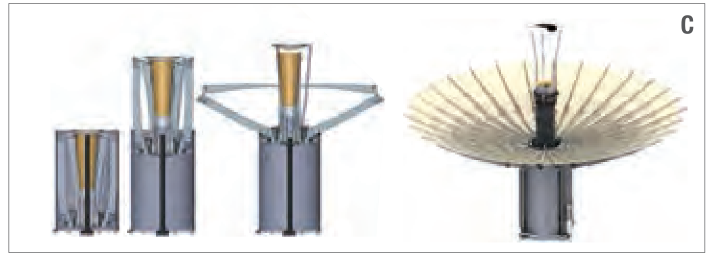
[A] The Mars helicopter would help scout for areas of highest scientific interest and choose the safest and fastest route to get there. [B] Prototype Mars helicopter has a 1.2-meter tip-to-tip diameter rotor system and weighs about 1.4 kg.

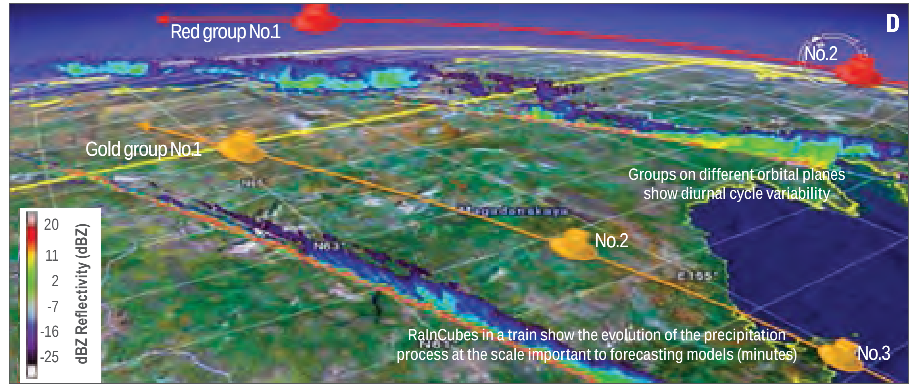


The prototype Mars helicopter rotors were successfully spun to full speed (2600 rpm). Lift forces measured matched **predicted levels, confirming vehicle flight** capability. Test was performed in JPL's 25-foot Space Simulator under Mars-like atmospheric conditions.

Imagine a fleet of connected helicopters surveying an area in great numbers, or adapting the technology to explore other worlds like **TITAN** and **VENUS**, and scaling up to carry other scientific payloads.







[A] July 2015, the radar instrument's performance was demonstrated on a DC-8 Aircraft for the first airborne test during the PECAN (Plains Elevated Convection at Night) campaign. The graphic shows a typical measurement obtained during the experiment. **[B]** The Ka-Band Parabolic Deployable Antenna (KaPDA) stows within a volume of 1.5U (10 x 10 x 15 cm). **[C]** The KaPDA design reliably deploys the antenna surface to within <0.15 mm RMS. **[D]** A RainCube constellation will make the first systematic observations of the dynamics of precipitation. Two to four convoys of RainCube CubeSats—the satellites in each convoy flying in formation between 60 and 240 seconds apart—would observe precipitating clouds globally at subseasonal time scales. **[right]** Principal Investigator Eva Peral inspecting radar electronics.

A first mission science goal would be the reconstruction of the statistics of precipitation as they vary during the diurnal and seasonal cycles across all latitudes from the Arctic to Antarctica. Better statistics mean better modeling to predict weather patterns across the globe.

RIDERS ON THE STORM

The Radar in a CubeSat (RainCube) project has developed the key technologies to build the first miniaturized Ka-band radar capable of profiling precipitation from a CubeSat platform. This technology enables the next generation of radar observations of weather phenomena from space.

The performance of the radar electronics has been demonstrated on a DC-8 during the Plains Elevated Convection at Night campaign. We can now actually consider deploying a constellation of identical RainCubes in various relative positions in low Earth orbit (LEO) to address specific observational gaps left open by current missions.

Current observations are sparse in time. They do not allow the observation of short time scale evolution of clouds and precipitation. RainCube enables the cost-effective deployment of multiple copies of the same instrument to fill this observational gap.

This novel 6U CubeSat architecture reduces the number of components, power consumption, and mass by more than one order of magnitude with respect to existing spaceborne radars.

Many scenarios relevant to NASA's Earth strategic goals are enabled by the proposed architecture. A mission science goal for RainCube will be to study the evolution of convective weather systems at the convective time scale by making 60- to 240-second observations of the same cloud to gather statistics about the triggers, evolution and effects of convection, and to study the dependence of these factors on the diurnal, subseasonal, and seasonal cycles by observing the same region at different times of the day during the same month. A single convoy of four RainCubes could gather enough observations across all latitudes from the Arctic to Antarctica during two years to make robust inferences; four convoys spread across the diurnal cycle would allow robust inferences about individual seasons. Better statistics mean better modeling to predict weather patterns across the globe along with their change at climate scales.

A constellation of RainCubes would also be a natural complement to other resources aiming at monitoring the evolution of weather systems, for example the Geostationary IR/VIS imagers, the NEXRAD network, and the Global Precipitation Measurement constellation.

We will soon see RainCubes riding the storms as it has been selected by the InVEST program and is funded to launch with NASA's CubeSat launch initiative as a Tech Demo in summer 2017.

This **NOVEL 6U** architecture reduces the number of components, power consumption and mass by over one order of magnitude with respect to the existing spaceborne radars.

THE UPSIDE OF UPSIDE DOWN EXPLORATIONS

JPL's research aims to build a bridge between exploring extreme environments in our own ocean and the exploration of distant, potentially habitable oceans elsewhere in the solar system.

How do you explore a place like Europa? We are almost certain there is a vast and potentially habitable ocean of water beneath the icy crust of this moon of Jupiter, but actually getting there and exploring it poses a huge challenge.

A team of scientists from JPL has been testing a new rover called the Buoyant Rover for Under-Ice Exploration (BRUIE) that can drive "upside down" on ice. When placed in water beneath an ice shelf, the rover floats to the top, and then uses two wheels to drive on the underside of the ice "ceiling." A suite of cameras, lights, and instruments can then be used to study the water below.

In 2012, a team took the rover to the thick ice shelf of the Arctic, thought to be a good analogue for Europa, with the vast ocean and thick ice mimicking what the moon could look like beneath its surface. The rover was able to communicate through the ice and, simulating a Europa mission, these communications were relayed through a satellite back to operators at JPL.

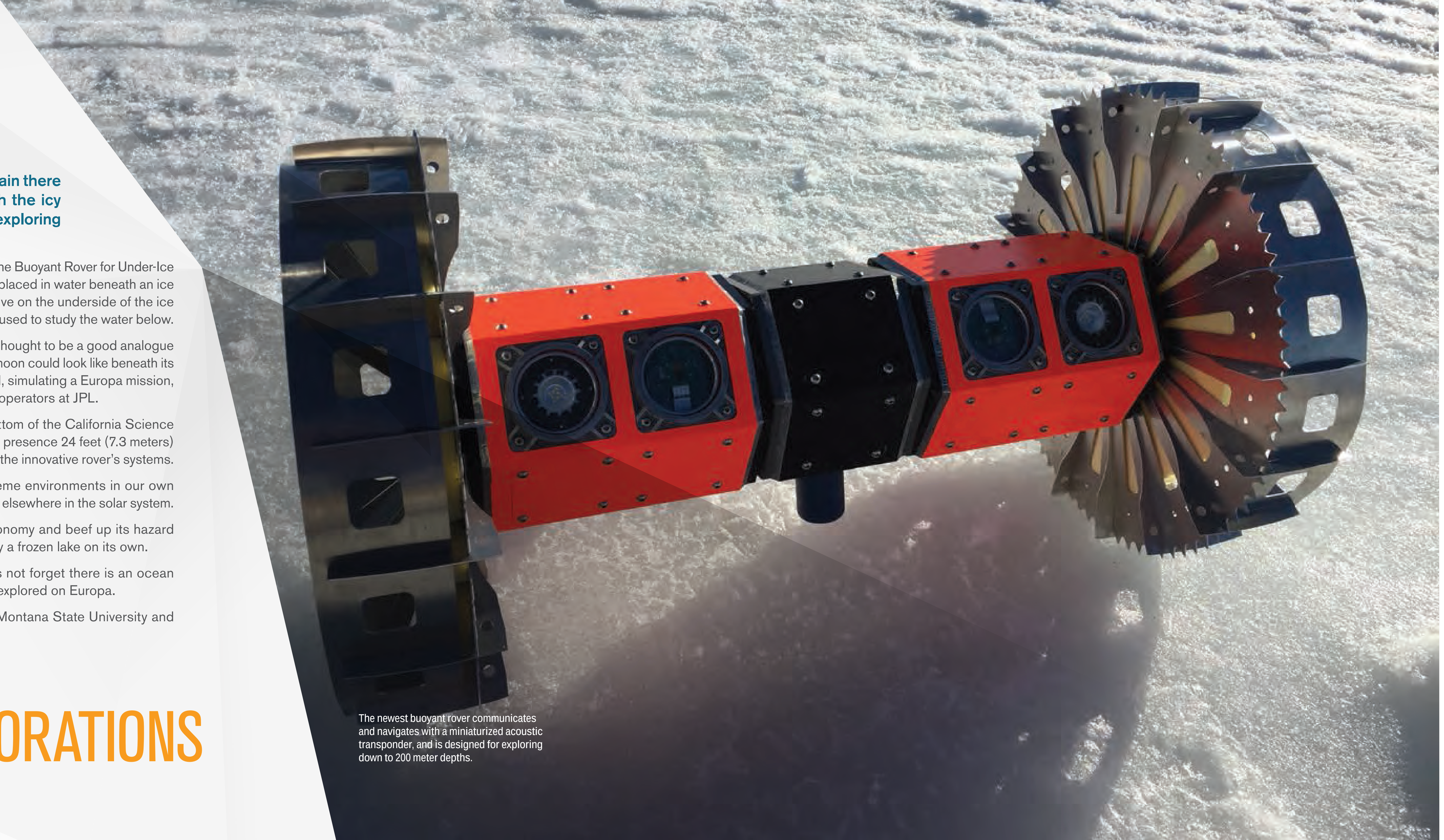
Another successful test was completed in June 2015 at the bottom of the California Science Center's 188,000-gallon aquatic tank in Los Angeles. The rover's presence 24 feet (7.3 meters) underwater at the science center helped researchers at JPL test the innovative rover's systems.

JPL's research aims to build a bridge between exploring extreme environments in our own ocean and the exploration of distant, potentially habitable oceans elsewhere in the solar system.

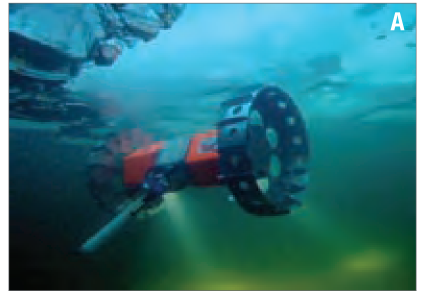
Researchers are currently working to increase the rover's autonomy and beef up its hazard avoidance, with an eye toward eventually letting the rover survey a frozen lake on its own.

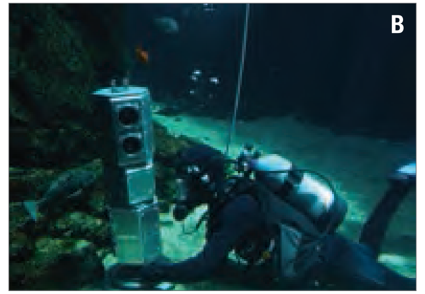
So while dribbles of water on Mars are all well and good, let's not forget there is an ocean containing more water than there is on Earth just waiting to be explored on Europa.

The BRUIE robot development was done in partnership with Montana State University and Desert Research Institute.



The newest buoyant rover communicates and navigates with a miniaturized acoustic transponder, and is designed for exploring down to 200 meter depths.





[A] The third generation rover demonstrated the capability for remote satellite control through a wireless ground station during two 30-hour under-ice deployments in the arctic. **[B]** Researchers tested an under-ice rover's systems at the bottom of a large aquatic exhibit at the California Science Center. **[C]** Recent deployments to Montana have demonstrated the rovers capability for long under-ice traverses and autonomy during remote operations.

The JPL Hedgehog rover prototype overlaid on an image of comet 67P.

SMALL HOPS TO BIG DISCOVERIES

[left] JPL Principal Investigator Issa Nesnas and Stanford engineers conducting hopping experiments aboard NASA's C-9 parabolic aircraft. **[A]** The basic concept is a cube with spikes that moves by spinning and braking mutually-orthogonal internal flywheels. [image credit] Stanford. **[B]** Hedgehog robot aboard NASA's C-9 aircraft lifting vertically off granular material (garnet sand). **[C]** The Stanford Hedgehog hopping/tumbling robot prototype on rugged terrain. [image credit] Prof. Marco Pavone, Stanford University.

Hopping, tumbling and flipping over are not typical maneuvers you would expect from a spacecraft exploring other worlds. But on a small body, such as an asteroid or a comet, the low-gravity conditions and rough surfaces make traditional roving all the more hazardous.

Enter Hedgehog: a new concept for a robot that is specifically designed to overcome the challenges of traversing small bodies. Researchers at JPL, Stanford University, and MIT are jointly developing the project.

The basic concept is a cube with spikes that moves by spinning and braking internal flywheels. The spikes protect the robot's body from the terrain and act as feet while hopping and tumbling. The spikes could also house instruments such as thermal probes to take the temperature of the surface as the robot tumbles.

In June 2015, two Hedgehog prototypes – one from Stanford and one from JPL – were tested aboard NASA's C-9 aircraft for microgravity research. During 180 parabolas, these robots successfully demonstrated several types of maneuvers for getting around on small bodies.

Hedgehog's simplest maneuver is a "yaw," or a turn in place. After pointing itself in the right direction, Hedgehog can either hop long distances using one or two spikes or tumble short distances by rotating from one face to another. The researchers also confirmed that Hedgehog can perform a "tornado" maneuver, in which the robot aggressively spins to launch itself from the surface. This maneuver could be used to escape from a sandy sinkhole or other situations in which the robot would otherwise be stuck.

The JPL Hedgehog prototype weighs about 11 pounds (5 kilograms), but the researchers envision that a flight version could weigh more than 20 pounds (9 kilograms) with instruments such as cameras and spectrometers.

The researchers are currently working on Hedgehog's autonomy by using an orbiting mothership to communicate with the robot, similar to how NASA's Mars rovers Curiosity and Opportunity communicate via satellites orbiting Mars. This mothership could release many robots at once or in stages, letting them tumble toward new discoveries.

The Hedgehog robot development was done in partnership with Stanford University and the Massachusetts Institute of Technology.

Two **HEDGEHOG** prototypes... were tested aboard NASA's C-9 aircraft for microgravity research... successfully demonstrated several types of maneuvers for getting around on small bodies.

FRED Y. HADAEGH
JPL Associate Chief Technologist
Dr. Hadaegh received his BSEE and MSEE from the University of Texas at Austin and 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).

JONAS ZMUIDZINAS
JPL Chief Technologist
Dr. Zmuidzinas received his BS in physics from Caltech in 1981 and his PhD in physics from UC Berkeley in 1987. A member of the Caltech faculty, Jonas has held a joint appointment JPL as senior research scientist since 2006 and served as director for the JPL Microdevices Laboratory from 2007 to 2011 before moving into his current role as JPL Chief Technologist. His research focuses on astrophysics at submillimeter and far-infrared wavelengths, including the development of superconducting detectors and multiplexing techniques as well as instruments for ground-based, airborne, and space telescopes.

PAUL BACKES | PG 54
Principal Investigator, BiBlade
Among the many awards Dr. Backes has received are the 1998 NASA Software of the Year Award Sole Runner-up and the 2004 NASA Software of the Year Award. At JPL, his current activities focus on planetary manipulation, sample acquisition, and sample handling.

ROHIT BHARTIA | PG 50
Principal Investigator, DEBI-t
Rohit Bhartia is a research scientist leading in-situ deep UV fluorescence and Raman instruments for astrobiology since 1998. He holds a BS in Bacteriology (UW-Madison), an MS in Biomedical Engineering, and a PhD in Geology (USC). In addition to subsurface microbial analysis he is the Deputy-PI on SHERLOC (Mars 2020).

ERIK S. BAILEY | PG 56
Principal Investigator, ProxOps
Erik has 15 years' experience at JPL in flight project Entry, Descent, and Landing (EDL) teams and research tasks including MER, MSL, Mars Phoenix, Autonomous Landing and Hazard Avoidance Technology, Low Density Supersonic Decelerator, and is currently the Technical Group Supervisor for the EDL Guidance & Control Systems Group.

ABHIJIT BISWAS | PG 48
Principal Investigator, OPALS
Abhijit has worked in the areas of laser spectroscopy and free-space laser communications for the past 20 years. He is currently with the Optical Communications Group and was the Ground Network Systems Engineer for the Mars Laser Communication Demonstration Project.

BOB BALARAM | PG 58
Principal Investigator, Mars Helicopter
At JPL, Bob has been active in the area of telerobotics technology development for Mars Rovers, planetary balloon aerobot systems, and multi-mission, high-fidelity spacecraft simulators for Entry, Descent and Landing and Surface Mobility.

JOHN R. BROPHY | PG 32
JPL Engineering Fellow
A graduate of Colorado State University, Dr. Brophy initiated the NSTAR Project that provided the ion propulsion for Deep Space 1, delivered the ion propulsion system for the Dawn mission, co-led the study at Caltech's Keck Institute that resulted in the proposed Asteroid Redirect Mission and is now its chief engineer.

IAN CLARK | PG 26
Principal Investigator, LDSD
Dr. Clark is the recipient of Presidential Early-Career Award for Scientists and Engineers – the highest honor bestowed by the United States Government on science and engineering professionals in the early stages of their careers. Ian was recognized for "exceptional leadership and achievement in the pursuit of advanced entry, descent and landing technologies and techniques for space exploration missions."

TARA ESTLIN | PG 16
Principal Investigator, AEGIS
The Supervisor of the Machine Learning and Instrument Autonomy group, Dr. Estlin received her PhD in computer science from the University of Texas at Austin. Tara and her team have successfully developed and infused the AEGIS software to provide intelligent targeting capabilities for the MSL and MER Missions.

STEVE CHIEN | PG 34
Principal Investigator, IPEX
Dr. Chien holds BS, MS, and PhD degrees from the University of Illinois. Steve is a four time honoree in the NASA Software of the Year Competition and has been awarded four NASA medals for his contributions to autonomous space systems. He has led the deployment of autonomy software for the Earth Observing One, Mars Exploration Rovers, and Rosetta missions.

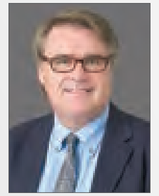
DAN GOEBEL | PG 32
Principal Investigator, Ion Propulsion
Honored for his contributions to low-temperature plasma sources for thin-film manufacturing, plasma materials interactions, and electric propulsion, Dr. Goebel is responsible for the development of high-efficiency electric thrusters, advanced long-life propulsion components, and thruster-life model validation for deep space missions.

COURTNEY DUNCAN | PG 14
Group Supervisor and Point of Contact, IRIS
Mr. Duncan holds a BM from Baylor University, BSEE with Honors from University of Houston, and MSEE from University of Southern California. He has experience in spacecraft communications and navigation systems, navigation and instrument real-time embedded software, and GPS and radiometric science investigations and instrumentation.

ROB GREEN | PG 30
Principal Investigator, Imaging Spectrometers
Rob is a science co-investigator on the CRISM imaging spectrometer for Mars and Instrument Scientist for the M3 imaging spectrometer on Chandrayaan-1 and MISE imaging spectrometer for Europa and Experiment Scientist for the NASA AVIRIS airborne imaging spectrometer. His research interest is imaging spectroscopy with a focus on advanced instrumentation, model-based spectroscopic inversions, as well as measurement calibration and validation.

TODD ELY | PG 24
Principal Investigator, DSAC
Dr. Ely plans and leads the Deep Space Atomic Clock (DSAC) investigation including managing the operational space mission. Todd represents the project to the sponsor, stakeholders, and the public and leads the team in analyzing the benefits of the clock for navigation and radio science and engaging potential DSAC customers.

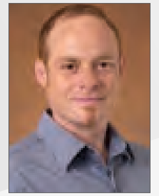
DOUGLAS HOFMANN | PG 28
Principal Investigator, Bulk Metallic Glass
Dr. Hofmann is a founding member of JPL's Materials Development and Manufacturing Technology Group receiving the Presidential Early Career Award for Scientists and Engineers in 2012 for his work in the development of bulk metallic glasses. Doug and his team do science research in metals and manufacturing for future JPL missions.



SIMON HOOK | PG 44

Principal Investigator, ECOSTRESS

Simon is the manager of the Science Division at JPL. His research is focused on improving our understanding of ecologic, geologic and hydrodynamic processes. He is the Principal Investigator for the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS). ECOSTRESS is planned for launch to the International Space Station in 2018.



ANDREW E. JOHNSON | PG 12

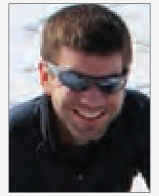
Principal Investigator, TRN

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

BRETT KENNEDY | PG 20

Principal Investigator, RoboSimian

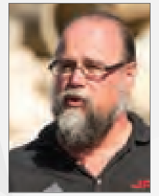
As a mechanical engineer specializing in robotic mobility and manipulation systems, Brett has developed a number of projects for flight and research. Notably, he is the Cognizant Engineer for the Robotic Arm aboard the Curiosity rover. He is currently the Principal Investigator for the RoboSimian robot and the Supervisor of the Robotic Vehicles and Manipulators Group.



ANDREW T. KLESH | PG 62

Principal Investigator, BRUIE

A graduate of the University of Michigan with five degrees and previously a postdoctoral fellow with JAXA, Dr. Klesh is currently chief engineer for several interplanetary small spacecraft missions. At JPL, Andy and his team are creating robotic platforms for the exploration of extreme icy-world environments, including deep-ocean landers and under-ice rovers.



JIM LUX | PG 18

Task Manager, FINDER

A licensed Professional Engineer, Jim managed the development of several microwave heartbeat sensors. He received the NASA Exceptional Achievement Medal for developing software radios for the International Space Station. Jim and his team are developing a cube-sat to measure Earth's ionosphere which will be launched in Spring 2017.

HARISH M. MANOHARA | PG 22

Principal Investigator, MARVEL

Dr. Manohara, an LSU graduate in engineering science, leads the nano and micro systems development at JPL. His areas of expertise include carbon nanotube and device miniaturization technologies for which he received JPL's Lew Allen award for technical excellence. He has led new device development for space, defense, medical, and commercial applications.

MICHAEL MCHENRY | PG 10

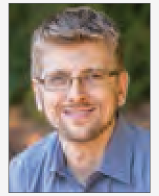
Principal Investigator, Mars Rover FastTraverse

Dr. McHenry has a PhD in Computer Science from USC and has worked on a range of mobile robotic systems ranging from small man-portable robots to MSL's Curiosity rover. Michael led the R&TD and MTP funded projects to mature FastTraverse technologies and to demonstrate them on MSL's vehicle system testbed.

ISSA A. NESNAS | PG 64

Principal Investigator, Hedgehog Flight Experiment

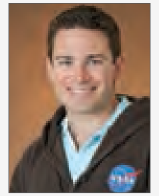
Dr. Nesnas is a principal technologist and supervisor of the Robotic Mobility group at JPL. He leads research in robotics and autonomy to explore extreme planetary terrains and microgravity bodies and supports flight projects. His Hedgehog Flight Experiment team included Robert Reid of JPL, Prof. Marco Pavone, and Benjamin Hockman of Stanford University.



JEFF NORRIS | PG 42

Principal Investigator, OnSight, ProtoSpace, SideKick

Dr. Norris founded and leads the JPL Operations Laboratory, creating tools that are revolutionizing the control of robots and spacecraft. A graduate of MIT and USC, he currently leads projects developing virtual and augmented reality tools for controlling Mars rovers, accelerating astronaut activities, and designing new spacecraft.



AARON PARNESS | PG 36

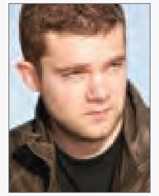
Principal Investigator, Gecko Adhesive

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, Aaron has experience in microfabrication, polymer prototyping, and traditional machining (both manual and CNC).

EVA PERAL | PG 60

Principal Investigator, RainCube

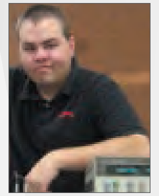
Dr. Peral received a PhD in telecommunications engineering from UPV (Spain) in 1998 and a PhD in electrical engineering from Caltech in 1999. Dr. Peral and her team are working on innovative approaches to miniaturize the radar electronics and ultimately reduce the cost of radar space missions.



RAUL POLIT CASILLAS | PG 52

Principal Investigator, 3D Printed Fabrics

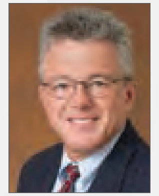
Raul is a graduate from ISU (MSc, France) in 2011 and UPV (Ms Arch, Spain) in 2008. He is an active member of AIAA with regular publications while he is working on his PhD research. With several awards from JPL and NASA for his innovative work, Raul works with a team experts at JPL to design and build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



ADRIAN TANG | PG 38

Principal Investigator, CMOS IMU Remote Sensors

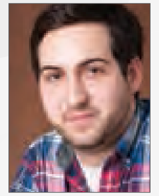
Dr. Tang obtained his PhD from UCLA in electrical engineering and is leading work at JPL focused on infusing CMOS system-on-chip technology from the gaming and mobile phone markets into spaceflight instruments. Adrian is an active contributor to many IEEE publications in the solid-state circuits and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



MARK THOMSON | PG 8

Principal Investigator and Architect, Starshade

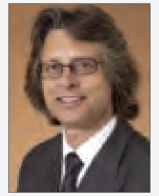
Mr. Thomson graduated from USC with BSME minoring in architecture. Since 2006, as a Chief Engineer for JPL mechanical systems, he has implemented numerous large precision deployable structures including the main antennas for SMAP, SWOT, NiSAR and a variety of SmallSats like RainCube. Mark and his team hope to contribute to the first direct detection of an eco-earth planet with the starshade.



ANDREW WILLIG | PG 46

Robotics Mechanical Engineer, Microspine Grippers

At JPL, Andrew is currently engaged in work on robotic vehicles and manipulators for use in various applications. He graduated with both his MS and BS in mechanical engineering from Carnegie Mellon University where he performed research in designing, building, and testing Modular Snake Robots.



JAKOB VAN ZYL | PG 6

Laboratory Associate Director

An electrical engineering graduate from Caltech, Jakob is a member of JPL's Executive Council and responsible for mapping out the JPL mission statement in the form of seven Quests. These Quests provide the framework for the initiation and development of JPL's missions and the benchmark for measuring success going forward.

Of all the planets studied by JPL, the quest to understand how Earth is changing may be the most significant. And although we have made major advances in our understanding of our home planet, it often seems as if we are still just scratching the surface.

The JPL 2015-2016 Technology Highlights document presents a diverse set of 29 technology developments selected by the Chief Technologist out of numerous 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 boundaries, and illustrate the broad spectrum of knowledge and technical skills at JPL that support these advances. While this document identifies important areas of technology development in 2015 and 2016, there are many other technologies that 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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