National Aeronautics and
Space Administration

Jet Propulsion Laboratory

Microdevices LABORATORY

LEADERSHIP, VISION & INNOVATION

2015-2016 | ANNUAL REPORT







MDL: a whole that is greater and more wondrous than the sum of its stellar, significant parts.







ABOUT THE COVER: How is Earth changing? This question, along with six others, comprise the seven Quests that help define the mission of NASA's Jet Propulsion Laboratory. Semiconductor laser instruments designed and developed at MDL have proven essential in the remote sensing of carbon dioxide and methane emissions in the polar regions. Research using these lasers has shown that a significant amount of methane is being released during the cold winter months, a revelation that is upending current carbon cycle thinking. Because methane is a major driver of atmospheric warming and global climate change, this data is proving to be extremely important in improving climate model predictions and planning for the future of this planet.

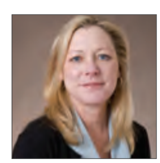
COVER PHOTO: Scientists believe a vast reservoir of methane may be locked in this Antarctic ice sheet. MDL's experience in technology development for methane detection should prove instrumental in helping scientists assess the effects of this potent greenhouse gas as it is released into the Earth's atmosphere.

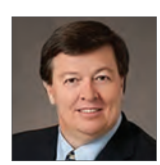



LEADERSHIP, VISION & INNOVATION

The **Jet Propulsion Laboratory's Microdevices Laboratory** has, since 1989, been a key player in JPL's dedicated efforts to create and deliver high-risk, high-payoff technology for NASA's future planetary, astrophysics, and Earth science missions. From the beginning, MDL has cultivated an environment that values and promotes leadership, vision, and innovation, through the talent, dedication, and hard work of MDL's founders, directors, scientists, researchers, and staff, along with sustained and insightful investments in infrastructure and equipment. Visit us online at **microdevices.jpl.nasa.gov**.






LEADERSHIP

Although there have been a number of exemplary leaders at MDL throughout its history, Dr. Jonas Zmuidzinas, who has served as JPL's Chief Technologist and the Director of MDL, stands out for his contributions to the sustained success of MDL. Initiatives he set in place at MDL continue to serve as the foundation for its path to the future.

REFLECTIONS ON MDL
JONAS ZMUIDZINAS

I RECENTLY had the opportunity to give the physics colloquium at the University of Illinois at Urbana-Champaign, where I spent two years as a postdoctoral fellow in 1988-89. That visit, during which department chair Dale Van Harlingen showed me the labs and equipment that I had used, brought back vivid memories of the terrific introduction to superconducting devices and microfabrication I received at Illinois. My visit also reminded me of how excited I was in 1990, as a new member of the Caltech faculty, to be able to start collaborating with an outstanding group of scientists and to make use of the wonderful facilities at the newly completed JPL Microdevices Laboratory (MDL).

My excitement about MDL remains undiminished more than 25 years later. I view the MDL as a treasure — for the nation, for NASA, for JPL, and for all of us who have the privilege to work there or to collaborate with those who do. The past 25 years have been amazingly successful — the MDL Visiting Committee agrees, calling it the "jewel in the crown." This is the legacy of former JPL Director Lew Allen and Chief Technologist Terry Cole, and the result of hard work by Carl Kukkonen, Satish Khanna, and many other dedicated JPLers. The MDL is a place that inspires us to dream, and more importantly, it provides us the ability to actually realize those dreams, as well as role models of those who have done so — **very much like JPL as a whole**.

I VIEW THE MDL AS A TREASURE – FOR THE NATION, FOR NASA, FOR JPL, AND FOR ALL OF US WHO HAVE THE PRIVILEGE TO WORK THERE OR TO COLLABORATE WITH THOSE WHO DO.

Similar thoughts were in my mind when I was asked in 2007 by JPL Chief Technologist Paul Dimotakis to assume the role of MDL Director. I was apprehensive about taking on this challenging role, but Paul had studied MDL carefully and proved to be quite persuasive. I was very fortunate to be able to work closely with Paul, with Tom Luchik, Annette Larson, Carl Ruoff, Bob Menzies, and others at the Division level, and with Marty Herman and Elizabeth Kolawa at the Section level; they took on the difficult but much-needed organizational re-integration of MDL, and their dedication and hard work re-energized MDL. I very much enjoyed my interactions with MDL Manager James Lamb — his commitment to MDL was exemplary, and his knowledge of the facility, and its history, was extensive. I was also very fortunate that Siamak Forouhar agreed to serve as Deputy Director; if any of our initiatives succeeded, it was a result of his energy, talent, and resourcefulness. My experience as MDL Director was defined by communication — with MDL staff, all levels of JPL's management, tours and visitors, our Visiting Committee, NASA, and with the outside world through vehicles such as presentations, our web site, and annual reports. My understanding of MDL's history, accomplishments, and future possibilities were greatly enriched, as was my appreciation for the excellence of MDL's staff.

Today, MDL plays an increasingly critical role in JPL's strategic quests, whether it is our goal to explore how Earth is changing, to investigate the possibility of past or present life on the planets or their moons in our solar system, to find extrasolar Earth-like planets, or to study the formation and evolution of our universe. Please join me in thanking MDL Director Chris Webster, Division Manager Tom Luchik, Section Manager Benny Toomarian, and all of the MDL staff for their commitment to carry forward this important and impressive legacy.

Dr. Jonas Zmuidzinas
JPL CHIEF TECHNOLOGIST

Dr. Christopher Webster
DIRECTOR
JPL MICRODEVICES LABORATORY

Dr. Thomas S. Luchik
MANAGER
SCIENCE & INSTRUMENTS DIVISION

LETTER FROM MDL

THIS YEAR'S MDL ANNUAL REPORT is devoted to JPL Chief Technologist Dr. Jonas Zmuidzinas, who has for many years provided the vision and support that continues to secure a prominent role for MDL long into the future, and ensures that we work on creative new technologies for NASA and other government agencies.

Dr. Jonas Zmuidzinas joined the California Institute of Technology faculty as an assistant professor of physics in 1990. He became associate professor in 1995, professor in 2000, and Merle Kingsley professor in 2010. Jonas Zmuidzinas has collaborated closely with JPL scientists and technologists since joining the Caltech faculty, and served as MDL Director 2007 to 2011 before moving into his current role as JPL Chief Technologist. Jonas laid the foundation of MDL's superconducting devices and materials group, and he continues to be a source of ideas for truly novel technologies over the nearly three decades he has been at Caltech. These technologies include superconducting mixers, the microwave kinetic inductance detector (MKID) that he invented in collaboration with MDL's Rick LeDuc and Peter Day, the microwave parametric amplifier, and the kinetic inductance parametric up-converter.

JONAS HAS WORKED WITH MDL'S SUPERCONDUCTING DEVICES AND MATERIALS GROUP AND CONTINUES TO BE A SOURCE OF IDEAS FOR TRULY NOVEL TECHNOLOGIES OVER THE NEARLY THREE DECADES HE HAS BEEN AT CALTECH.

This pioneering work on superconducting mixers has created new areas of applications from quantum computing to optical communication, with high-visibility science impact in outer planet atmospheres, star formation, dark matter, and the structure of the Universe. Dr. Zmuidzinas is a brilliant researcher and innovator, and has been a wonderful leader and mentor who inspires and encourages us all at MDL.

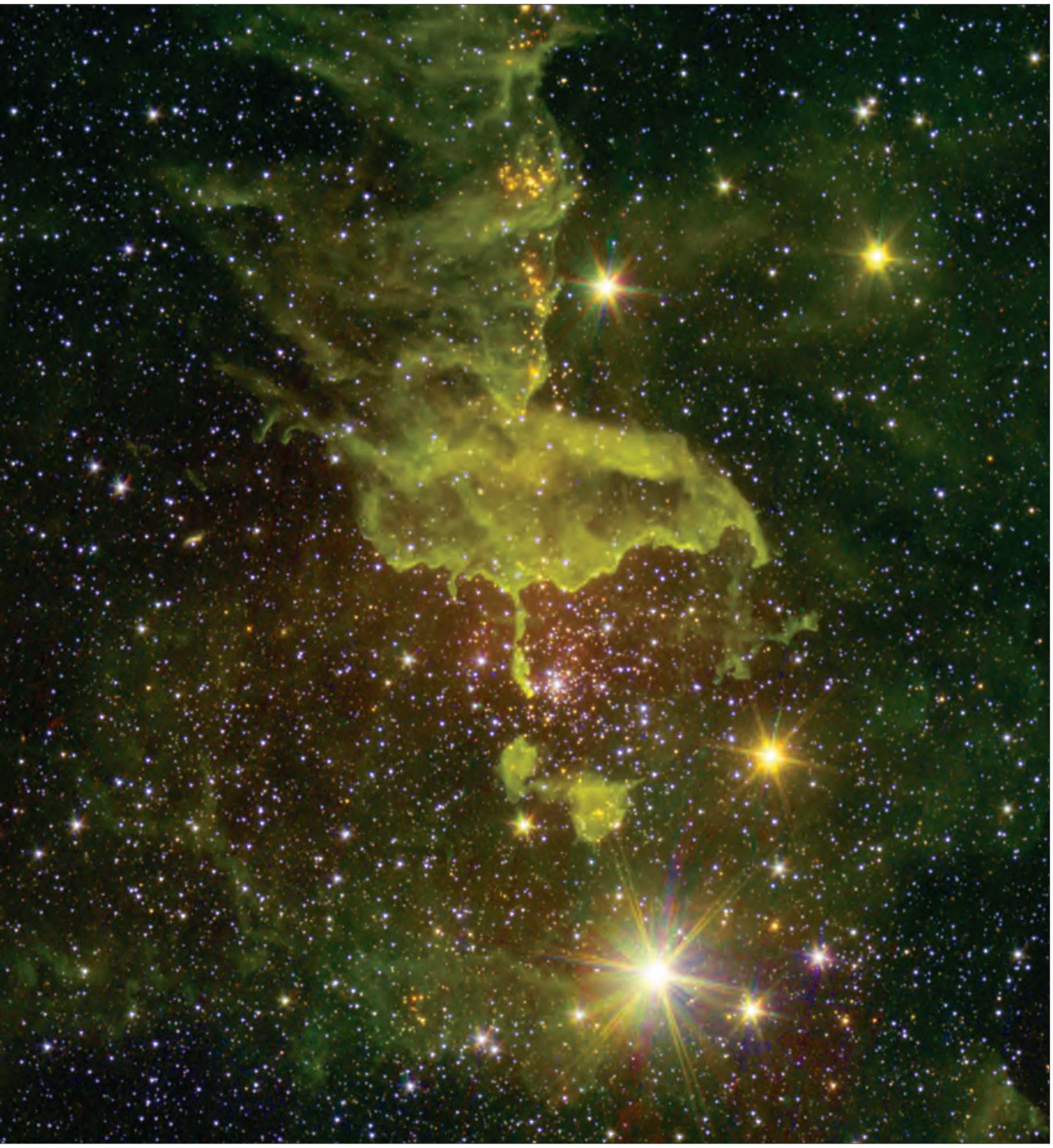
With the imminent retirement in June 2016 of our JPL Director Dr. Charles Elachi, it is no doubt the end of an era, but we are excited about the new era beginning under our new JPL Director Dr. Michael Watkins. During his 22-year career at JPL, Dr. Watkins has held major leadership roles in a number of high-profile missions including MSL, Cassini, Mars Odyssey, GRAIL, and GRACE. He served as Manager of JPL's Science Division and Chief Scientist for the Engineering and Science Directorate, and is returning to JPL after a short stay at the University of Texas as the Clare Cockrell Williams Centennial Chair in Aerospace Engineering.

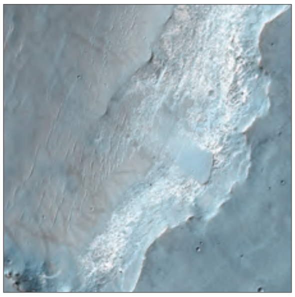
Under Dr. Watkins' leadership of JPL, we look forward to an exciting, challenging, and highly-productive future of creating new technologies that enable NASA space missions in Earth, planetary, and astrophysics discoveries, and pioneering technology development for many areas of national importance, from medical applications to national security.

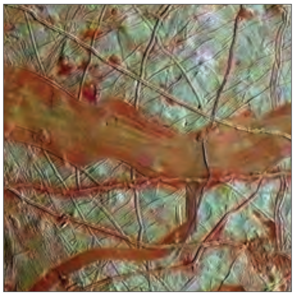
We join our Chief Technologist Dr. Zmuidzinas, our university, industrial, defense, and commercial partners, and the highly-skilled staff of MDL in celebrating our incredible achievements to date across a diverse range of applications. We welcome our new JPL Director with our promise to delight him with the innovative mission-enabling technologies to be developed by MDL in this new era under his leadership.

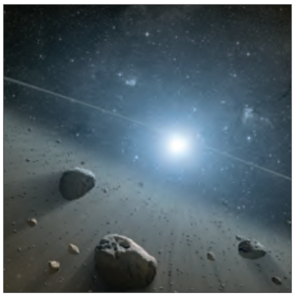
JPL QUESTS

As JPL pursues some of NASA's most challenging scientific and technical quests, technological advances achieved at the Microdevices Laboratory (MDL) serve critical nano- and microtechnology needs for finding answers, and for crafting pathways for new explorations.









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 potentially 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 volcanic 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.

MDL SUCCESS STORIES 2015-2016

MDL's leadership, vision, and innovation is exemplified in its rise to the challenge of the JPL Quests through its contributions to these technologies.

Using ultra-narrow linewidth infrared lasers, TLS measurements of isotope ratios in methane, water, and carbon dioxide have revealed details about the planet's past environment.

1 | HAS THERE EVER BEEN LIFE ELSEWHERE IN OUR SOLAR SYSTEM?

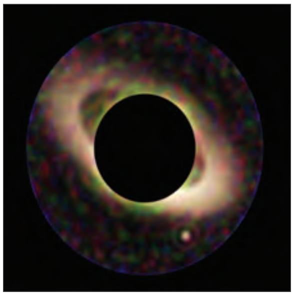
LASERS ON MARS KEEP GOING

Aboard the Mars Science Laboratory Curiosity rover, the Tunable Laser Spectrometer–using lasers developed and space-qualified at MDL–is paving the way for semiconductor lasers to play an important role in future planetary science missions with applications in spectroscopy, laser altimeters, and metrology.

2 | ARE THERE PLANETS LIKE EARTH ELSEWHERE IN THE UNIVERSE?

IMAGING GIANT EXOPLANETS

Techniques developed by MDL for fabricating two types of starlight-occulting masks were successfully tested in 2015. The NASA Wide-Field Infrared Survey Telescope (WFIRST) coronagraph will be the first glimpse of planetary systems (exoplanets and dust disks) in reflected light around nearby stars.

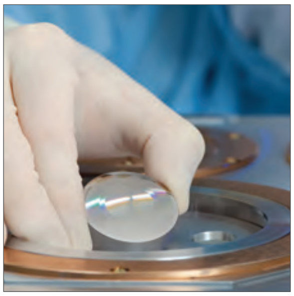


Simulation of expected image of a planet (at about 5-o'clock) with zodiacal dust cloud. This technology could be aimed at finding habitable Earth-like planets around nearby stars.

5 | WHAT CHANGES ARE HAPPENING TO OUR PLANET?

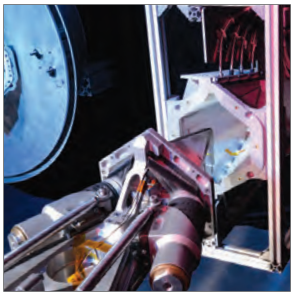
CUSTOM DIFFRACTION GRATINGS

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, including our own. JPL has been at the forefront of this field for decades. MDL has developed new processes that push the limits of electron-beam lithography to fabricate high-performance, shaped-groove diffraction gratings –an essential component in delivering compact, higher performance imaging spectrometers.



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

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



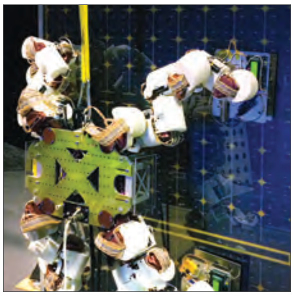
Fiberscopes acquire sample images in the sample measurement chamber.

COMET SAMPLING TOOL

BiBlade is an innovative sampling tool with two blades that could be driven into a small body's surface to acquire and encapsulate the sample in a single, quick sampling action. It was developed and validated at MDL for a future sample-return mission to a small body surface such as a comet.

ZERO-GRAVITY EXPERIMENTS

Using MDL's rapid-prototyping facilities, JPL researchers fabricated sheets of a reusable gecko-like material. The synthetic gecko toes on this innovative material are capable of supporting substantial loads on smooth surfaces commonly used on spacecraft–fiberglass, aluminum, mylar, and solar panels.



The Limbed Excursion Mechanical Utility Robot (LEMUR) using synthetic gecko to crawl on a solar panel in the lab.

7 | CAN WE USE JPL'S EXPERTISE TO SERVE OUR NATION?

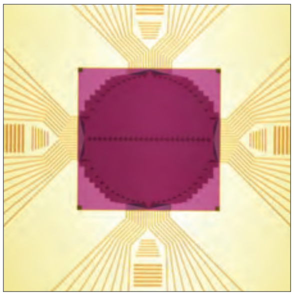
Laboratory prototype of MARVEL, one of the world's smallest, steerable 3D cameras.

DIGITAL IMAGING AND 3D ENDOSCOPY

MDL is involved in the next generation of endoscopic tools, bringing together sweeping advancements in digital imaging, 3D endoscopy, and smart micro/nano technology. With MDL's Multi-Angle Rear-Viewing Endoscopic Tool (MARVEL), a surgeon will be able to continuously sweep over 120 degrees, allowing a 3D view of the operating field from different angles.

SUPERCONDUCTING DETECTORS

Information can never travel faster than the speed of light, but through optical communications research, we can increase the amount of information we send back from space. JPL and MDL are developing NASA's Deep Space Optical Communication (DSOC) project to meet the ever-increasing demand for returning larger volumes of data from space.



Optical microscope image of a free-space-coupled 64-pixel SNSPD array for the DSOC ground receiver.

JPL MICRODEVICES LABORATORY VISITING COMMITTEE






Meeting every two years to review the ongoing work at MDL and make valuable suggestions for future directions, the Visiting Committee has recognized the leadership, vision, and innovation of MDL. The board assessment to-date has been a great value to MDL in pursuing the highest quality research and development programs targeted toward the key scientific and technical goals of interest to NASA and our other sponsors. This is apparent in the following quote from the 2015 committee report:

> *The committee recognizes MDL as a key national asset with unique state-of-the-art capabilities and staff well focused on space applications of micro- and nanotechnologies... Much of the work presented is absolutely world-class, and the staff is enthusiastic and dedicated to advancing the state-of-the-art in their area to make a difference for JPL and NASA. It was evident to the committee that the blend of scientific mission and technical challenges is working for JPL/MDL (and)... this team continues to develop world-leading processes and capabilities. In many cases, MDL work defines the state-of-the-art. MDL is truly the "**jewel in the crown**."*

DR. THOMAS L. KOCH, COMMITTEE CHAIR
Dean of College of Optical Sciences and Professor of Optical Sciences—University of Arizona

DR. BARBARA WILSON, COMMITTEE CO-CHAIR
Retired Chief Technologist—Jet Propulsion Laboratory

DR. EUSTACE DERENIAK, FORMER CHAIRMAN
(2008-2015) Professor of Optical Sciences, Electrical and Computer Engineering—University of Arizona

MR. ROBERT BAUER
Deputy Associate Director and Program Manager —NASA's Earth Science Technology Office (ESTO)

DR. SANJAY BANERJEE
Director of Microelectronics Research Center and Professor of Electrical and Computer Engineering—University of Texas at Austin

DR. JED HARRISON
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Professor of Applied Physics —California Institute of Technology

DR. REGINA RAGAN
Professor of Chemical Engineering and Materials Science —University of California, Irvine

DR. DONALD REAGO
Director of Communications, Electronic Research, Development and Engineering Center (CERDEC) —Night Vision and Electronic Sensors Directorate (NVESD)

DR. ROBERT TREW
Division Director of Electrical, Communications and Cyber Systems (ECCS)—National Science Foundation

DR. ROBERT WESTERVELT
Professor of Physics and Applied Physics —Harvard University









CONTENTS

12.... SEMICONDUCTOR LASERS

18.... OPTICAL COMPONENTS

22.... ADVANCED DETECTORS, SYSTEMS & NANOSCIENCE

28.... INFRARED PHOTODETECTORS

32.... SUPERCONDUCTING MATERIALS & DEVICES

38.... SUBMILLIMETER–WAVE ADVANCED TECHNOLOGY

44.... NANO & MICRO SYSTEMS

50.... IN SITU INSTRUMENTS

54.... INFRASTRUCTURE & CAPABILITIES

57.... MDL EQUIPMENT COMPLEMENT

59.... PUBLICATIONS, NEW TECHNOLOGY REPORTS, PATENTS, BOOK CONTRIBUTIONS, INVITED TALKS, & SPECIAL RECOGNITION

"Continuing investments by **NASA** and **JPL** have enabled the MDL semiconductor laser development to make far-reaching impacts in key areas of science and technology.

SEMICONDUCTOR LASERS

LEFT. The semiconductor laser development at MDL was pioneered and lead by Siamak Forouhar since the beginning of MDL. The current team [L to R] consists of Ryan Briggs, Siamak Forouhar, Mahmood Bagheri, Cliff Frez, and Mathieu Fradet. The team members' diverse backgrounds—from industry and academia in electrical engineering, materials science, chemical engineering, and physics—reflect the interdisciplinary nature needed for laser design, fabrication, and space qualification of a variety of semiconductor lasers, and for packaging them.

FAR-REACHING IMPACT

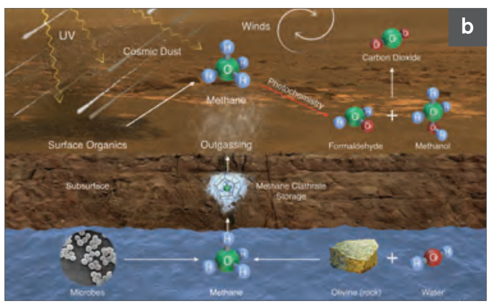
MDL'S PIONEERING WORK ON DEVELOPMENT AND SPACE QUALIFICATION OF SEMICONDUCTOR LASERS HAS ENABLED A NEW ERA IN PLANETARY AND EARTH ATMOSPHERIC STUDIES.

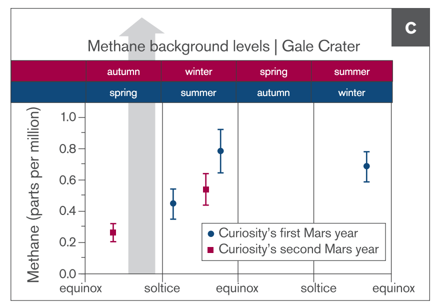
JPL and NASA share a long history of flying tunable laser spectrometers on Earth and planetary missions for atmospheric gas analysis. Due to the interest and world class capabilities at JPL developing laser-based instruments, the semiconductor laser technology development was one of the initial research areas at MDL.

Continuing investments by NASA and JPL have enabled the MDL semiconductor laser development to make far-reaching impacts in key areas of science and technology. The most notable achievement in planetary science has been to successfully develop and qualify infrared lasers for the tunable laser spectrometer (TLS) instrument on the Mars Curiosity rover to analyze atmospheric gases like methane and isotope ratios. Looking ahead, the Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) concept is under consideration for the next Discovery Mission selection. DAVINCI's Venus tunable laser spectrometer instrument will measure the abundance and isotopic composition of H_2O/CO_2, OCS, and SO_2 using MDL mid-infrared lasers emitting at 2.64, 4.82, and 7.42 µm, respectively. Ongoing efforts to mature long-wavelength lasers operating near 10 µm will be enabling for the proposed New Frontiers Saturn Probe mission, which has the high-priority objective of measuring isotope ratios in atmospheric NH_3.

For Earth science studies, high-power, wavelength-stable lasers developed at MDL have been integrated with NASA-sponsored spectrometers aboard high-altitude aircraft in order to validate climate science models. Recently, an instrument built by the group of Professor James Anderson of Harvard University used 2.65-µm lasers developed at MDL to measure HDO concentrations in Earth's upper atmosphere. The group has also developed high-power, narrow-linewidth lasers emitting near 2 µm to support ongoing development of space-based active lidar systems for measuring CO_2 profiles. In the area of environmental sensing, fire safety systems aboard the International Space Station, and, prospectively, deep-space human exploration missions, require an advanced combustion product monitor (CPM) to track concentrations of toxic gases generated by accidental fires. Analyses of prior spacecraft fires and pyrolytic events by NASA toxicologists have identified CO and HCN as the most important target gases. The MDL laser team has developed a prototype CPM instrument using mid-infrared lasers capable of monitoring CO and HCN, as well as HCl, HF, and CO_2, at part-per-million levels. Beyond NASA, sensor technologies initially developed using JPL-built lasers have formed the backbone of companies operating in areas that include oil and gas pipeline monitoring, industrial process control, aircraft safety, and medicine. The MDL semiconductor laser group continues to push ahead by addressing needs that are not yet met by component vendors in the marketplace. Current efforts include the development of semiconductor-based optical comb sources operating near 3 µm, which can serve as broad-wavelength sources for dynamic and/or multi-species measurements, as well as long-wavelength quantum cascade laser technology with exceptionally low power consumption, which enables the implementation of compact spectrometers on mobile platforms such as hand-held sensors, autonomous aircraft, and low-cost spacecraft.

right. Mars' Gale Crater is a fascinating place to explore because of the mountain of layered materials in the middle. The layers tell a story about what Mars was like in the past, perhaps spanning much of the history of the red planet.





a. Dr. Webster holds a laboratory duplicate of the Mars TLS instrument to be used for testbed studies. **b.** This illustration portrays possible ways that methane might be added to Mars' atmosphere (sources) and removed from the atmosphere (sinks). **c.** NASA's Curiosity Mars rover has detected fluctuations in methane concentration in the atmosphere, showing episodic high-level release and also a seasonal dependence to the background values, implying activity in the modern environment of Mars.

MDL LASERS ON MARS

"TLS has been an incredible success for MDL, the instrument division, and JPL. I am so very proud of the TLS team (design, fabrication, integration, and test) who have ensured this instrument working SO well and SO long so far from home." —C. Webster, TLS PI. After nearly 3 years on Mars, TLS is alive and well, and continues to produce high-impact science on Curiosity. The instrument is performing EXACTLY as it did some 4 years ago pre-ship, with no deterioration in performance or capability. As a result of its success, TLS is in a Step 2 competition for the DAVINCI (Goddard Space Flight Center) Discovery Mission, and is part of concept studies for New Frontiers Venus and Saturn Probe missions. We are currently building a mini-TLS for CubeSat and other small platforms under internal research and technology development funding, enabled by our successful mini-digital electronics efforts. As far as science, the TLS results have been the principal subject of six papers in the journal *Science*, and generated several hundred news stories across the world. Some highlights are:

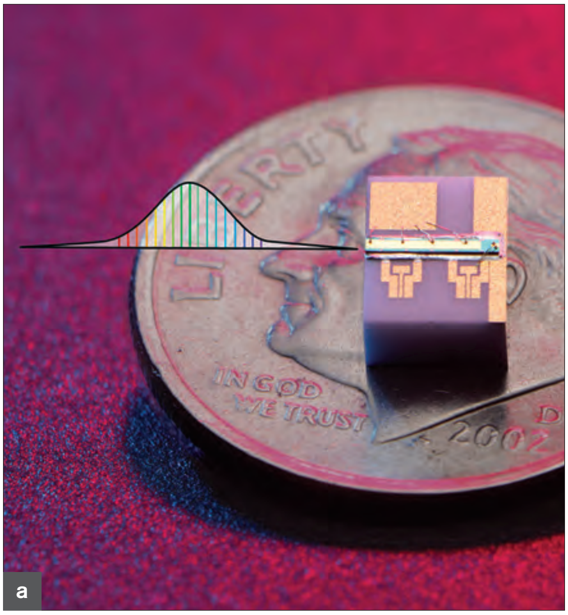
1. Mars methane: in addition to observing a pulse of high (7 ppbv) methane over one Mars year ago that did not return, TLS has been monitoring sub-ppbv background levels to reveal a seasonal dependence that may establish the connection between UV radiation and methane production from organic infall.
2. D/H in water: Measurements showed that D/H values in water evolved from rock pyrolysis that were only 3 times those on Earth (compared to 6 times those in the Mars atmosphere). This indicates that at an earlier time the Gale Crater region had significant liquid water, with a global equivalent layer of ~150 m.
3. Atmospheric CO_2 isotope ratios at unprecedented accuracy: Isotope ratios in C and O in CO_2 show that the Mars atmosphere has changed little in 4 billion years. It is a key result for models of planetary evolution that the 13C/12C results form a balance between atmospheric loss and carbonate formation.
4. Methane isotopic ratios in 13C/12C from methane evolved from rock samples show clear differences between sample groups, and may reflect the presence of surface organics.
5. Fine spectral line structure seen in rock pyrolysis as "mystery lines" are identified with Cl_2O_6 and represent production from degradation of surface perchlorates.
6. As a bonus, TLS detects a strong HF line produced from rock pyrolysis that is being used to identify fluorine-containing minerals.

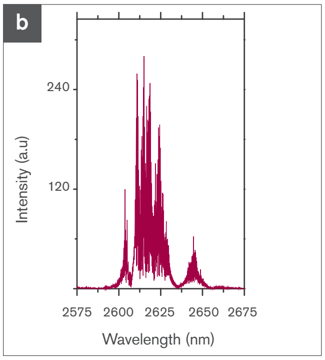
OPTICAL FREQUENCY COMBS FOR BROADBAND, TIME-RESOLVED SPECTROSCOPY

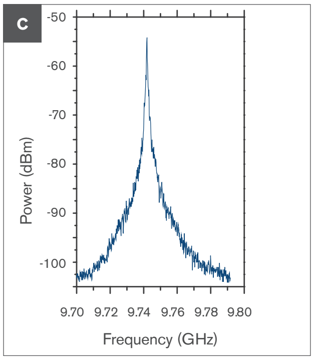
MODERN SPECTROSCOPIC SYSTEMS can accurately measure the real-time dynamics of mixed atomic and molecular species, assuming the availability of a broadband source in the relevant wavelength band. Recent experiments using multi-heterodyne frequency-comb Fourier-transform spectroscopy (also called dual-comb spectroscopy) have demonstrated that precisely spaced spectral lines of an optical comb can be harnessed to sensitively acquire highly multiplexed molecular spectra. Motionless Fourier interferometers based on two combs with slightly mismatched frequencies have opened new opportunities in physics, chemistry, biology, and industry and have surpassed the precision and speed of Fourier spectrometers (molecular fingerprinting with part-per-trillion (ppt) range sensitivity and sub-millisecond acquisition times).

JPL and partners at Naval Research Laboratory (NRL) and Rice University are developing an Electrically Pumped Interband Cascade (EPIC) optical frequency comb based on a small form-factor and highly efficient passively mode-locked interband cascade laser. The compact EPIC source operating in the 3-4 μm wavelength range will be an enabling technology for the next generation of spectroscopic chemical sensor systems that can accurately measure the real-time dynamics of mixed atomic and molecular species with weak spectral features. Such an optical frequency comb operating in 3-4 μm range is an important tool for spectroscopy, where the fundamental rotational–vibrational bands of most light molecules are found.

The simple design, ease of use, and performance metrics of our optical source will facilitate the implementation of complex spectroscopic techniques such as dual-frequency-comb spectroscopy and asynchronous optical sampling in the mid-IR spectral range and will open novel industrial opportunities.

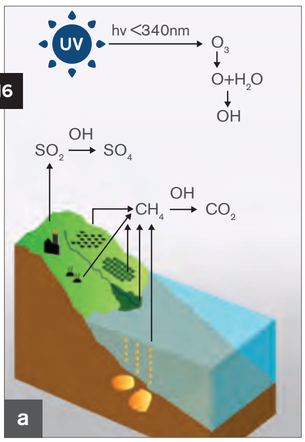


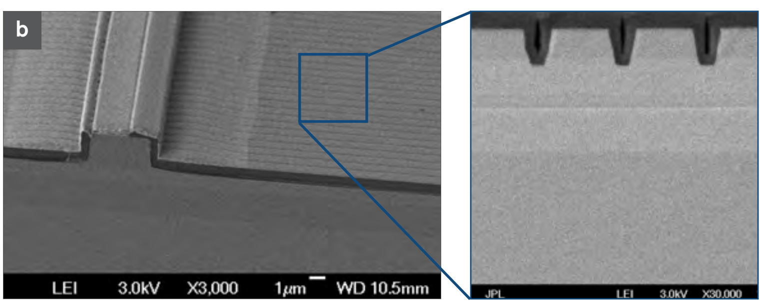




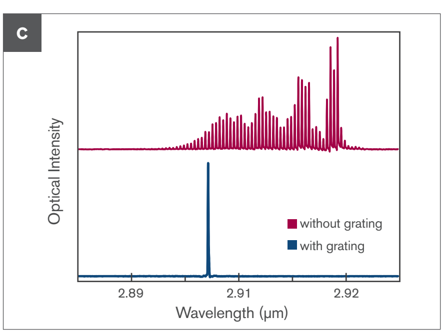
a. Optical image of an interband cascade comb laser (ICL). It features a split-contact gain/saturable-absorber architecture, in which the top metal contact of the ICL is divided into a longer forward-biased portion, and a relatively shorter reverse-biased portion that functions as a saturable absorber. The saturable absorber drives the multimode operation and phase locks the longitudinal modes of the ICL cavity. **b.** Optical spectrum of an ICL-comb collected using a Fourier transform infrared (FTIR) spectrometer. **c.** RF spectrum acquired with an electrical spectrum analyzer (span = 10 MHz, RBW = 1 kHz). The RF spectra are centered around 9.75 GHz, corresponding to the RF beatnote generated by a 4-mm-long cavity. The large amplitude of this tone results from the mutual beating of adjacent modes in the optical spectrum, while its narrow width (~ 50) indicates that the random relative phase drift among the modes, which is a characteristic of mode-locked lasers, is small.

Earth's atmosphere viewed from the International Space Station. Recent studies show that global temperatures remain stable in the long run unless they are pushed by outside forces, such as increased concentrations of greenhouse gases due to human activity.





a The OH radical plays an important role in the photochemical control of ozone density in the atmosphere and reacts strongly with gas species in the troposphere as a main oxidizing agent. Methane (CH_4) released in the atmosphere from methane hydrate deposits on the sea floor, and carbon monoxide (CO) released mainly from burning of biomass and fossil fuel use, react with OH to form CO_2. The increase in CO emissions due to human activity has led to a decrease in available OH radicals to oxidize CH_4. Being able to measure OH in the atmosphere with a high degree of accuracy is critical as an indicator of increasing CH_4 levels, which can contribute significantly to the greenhouse effect. The decrease in reflectivity of light from Earth's surface caused by the melting of ice sheets can lead to a decrease of OH due to the photochemical reaction of ozone with UV light, leaving a greater amount of CH_4 and SO_2 in their original form in the atmosphere.

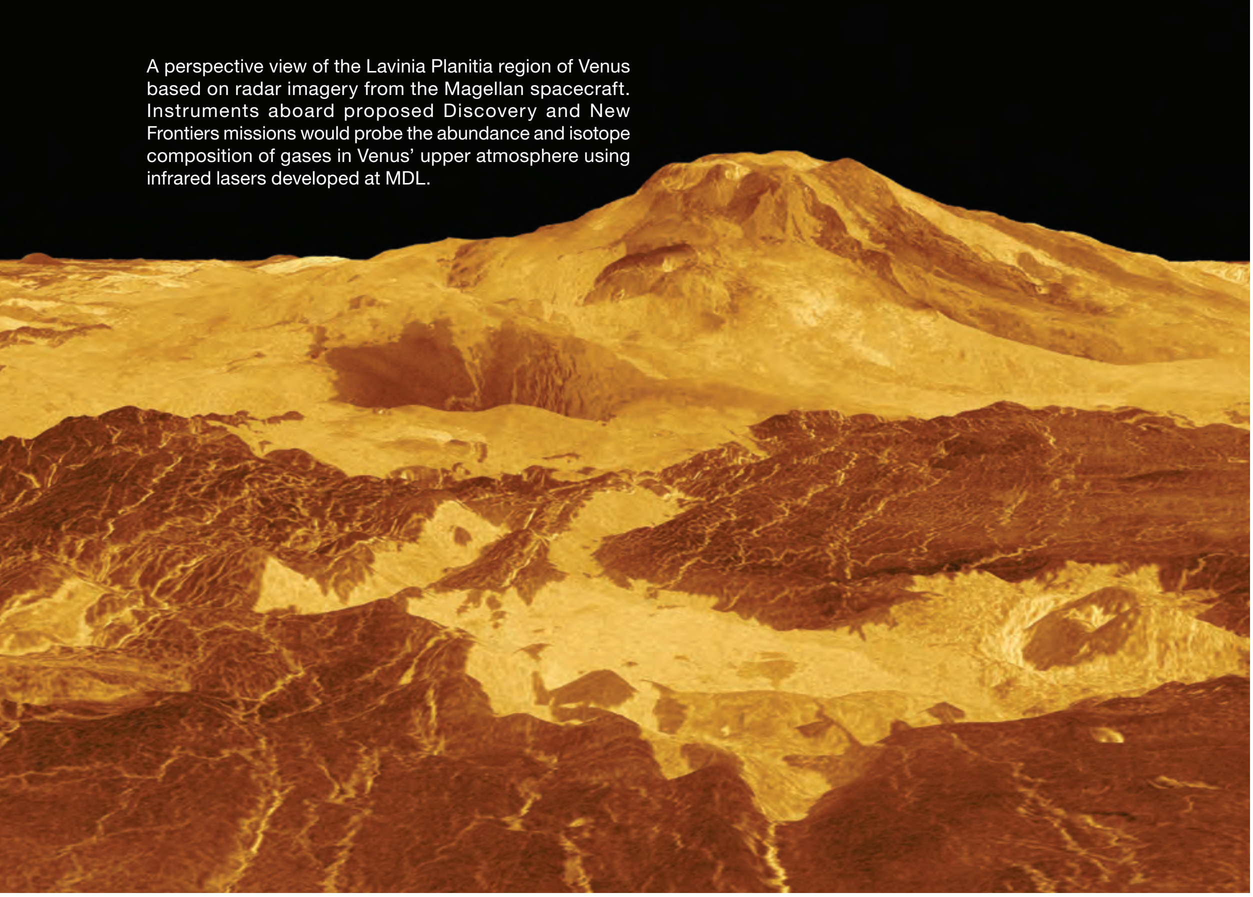


b Scanning electron micrograph of a type-I cascade diode laser fabricated at MDL. Inset: Cross-sectional view of the laser Bragg grating. **c** Laser emission spectra showing the impact of a well-fabricated grating.

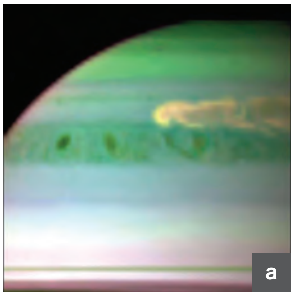
TYPE-I CASCADE DIODE LASERS FOR ATMOSPHERIC SCIENCE

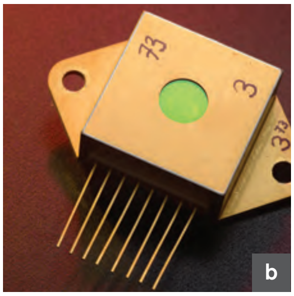
THERE IS A NEED WITHIN NASA for instruments that can be deployed on small aircraft, balloons, and planetary probes to accurately detect reactive radical intermediates in the troposphere. Those radicals, especially hydroxyl (OH), have a great impact on the depletion of ozone and react strongly with greenhouse gases. New approaches enabled by mid-infrared lasers have opened the door for robust, portable instruments capable of detection limits near a part per million. For OH measurements, lasers are required that emit across fundamental rovibrational absorption bands near 2.9 μm with tens of milliwatts of single-mode output power.

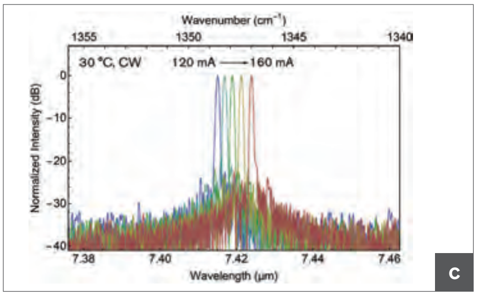
To develop these laser sources, the MDL semiconductor laser group teamed up with State University of New York at Stony Brook, a leader in the development and epitaxial growth of type-I diodes and cascade diodes emitting in the 2 to 4 μm wavelength. This collaboration has led to the first single-frequency, laterally coupled, distributed feedback type-I cascade diode laser. To facilitate the study of the tropospheric impact of OH radicals on ozone depletion and the cycle of greenhouse gases in Earth's atmosphere, in the past year, we delivered a single-frequency, high-power laser emitting at 2.9 μm to JPL scientists.



A perspective view of the Lavinia Planitia region of Venus based on radar imagery from the Magellan spacecraft. Instruments aboard proposed Discovery and New Frontiers missions would probe the abundance and isotope composition of gases in Venus' upper atmosphere using infrared lasers developed at MDL.







a. This false-color infrared image shows clouds of large ammonia ice particles dredged up by a powerful storm in Saturn's northern hemisphere. **b.** A low-dissipation quantum cascade (QC) laser fabricated at MDL and packaged with integrated collimation optics. This device emits at 7.42 µm and is designed to target absorption lines of SO_2 for a proposed laser spectrometer instrument on in situ science missions to Venus. **c.** Emission spectra measured from a QC laser fabricated at MDL for detection of SO_2.

LOW-POWER-CONSUMPTION QUANTUM CASCADE LASERS FOR IN SITU PLANETARY SCIENCE

FOLLOWING THE SUCCESS of the tunable laser spectrometer (TLS) aboard the Mars Curiosity rover, laser-based spectroscopy instruments are expected to play a vital role in future planetary science missions. By selectively targeting absorption lines of key atmospheric gases and their less abundant isotopologues across the infrared spectrum, next-generation TLS instruments can provide valuable information on the composition and origins of bodies throughout the solar system. Lasers emitting in the mid- to long-wavelength infrared regime between 4 to 10 µm are required to access absorption lines of several compounds of importance for planetary science; however, such lasers are currently unavailable with the low power consumption required for in situ instrument payloads. We are developing single-mode lasers based on semiconductor quantum cascade (QC) structures with emission wavelengths in the 4 to 10 µm spectral range. The laser sources are designed specifically for module power consumption below 1 W, while targeting molecular absorption lines of interest for high-priority planetary missions. These infrared lasers will enable the development of tunable laser spectrometers for New Frontiers and Discovery missions, including instruments designed to measure the abundance and isotopic composition of sulfur dioxide in the atmosphere of Venus, and isotopologues of ammonia and phosphine on Saturn.

OPTICAL COMPONENTS

> “**JONAS ZMUIDZINAS** was instrumental in creating mechanisms for maintaining equipment funding and for hosting periodic external reviews to provide feedback and support for our technologies.”

Daniel Wilson, Robert Green, Richard Muller, and Pantazis Mouroulis in the imaging spectrometer testbed laboratory [L to R].

PRECISION AND EFFICIENCY

The Optical Components Group develops electron-beam lithography techniques to fabricate nanostructures that enable JPL optical instruments to perform novel measurements and achieve unmatched performance. We began developing our unique fabrication techniques in the early 1990s with the leadership and innovation of Paul Maker. Our early efforts led to the successful development of grayscale e-beam techniques for fabricating gratings with precisely shaped grooves on curved surfaces. Such gratings enabled the realization of compact, high-performance Offner and Dyson imaging spectrometers with multiple-octave bandwidths operating at wavelengths from ultraviolet to long-wave infrared.

MDL'S PRECISION OPTICAL DEVICES ARE AT THE HEART OF INSTRUMENTS THAT REALIZE NEW CAPABILITIES ACROSS WAVELENGTHS FROM THE ULTRAVIOLET TO LONG-WAVE INFRARED WAVELENGTHS.

Our gratings have been used in many airborne and spaceborne spectrometer instruments including Hyperion (Earth Observing 1), CRISM (Mars Reconnaissance Orbiter), ARTEMIS (TacSat-3), and Moon Mineralogy Mapper (Chandrayaan-1). Over the years, we have developed novel e-beam exposure techniques, substrate mounting fixtures, and pattern preparation software to allow fabrication of complex diffractive optics on a wide variety of substrate shapes and materials.

Critical to our fabrication capabilities are high-performance electron-beam lithography tools that are expensive and require periodic maintenance. As MDL's first Director, Jonas Zmuidinas was instrumental in creating mechanisms for maintaining equipment funding and hosting periodic external reviews to provide feedback and support for our technologies.

These activities were instrumental in developing management support for the procurement of our newest e-beam tool, the JEOL 9500FS, which will be installed during the coming year. The new system will provide enhanced precision, increased speed, and expanded size to enable fabrication of state-of-the-art nanostructured optical components for next generation instruments.

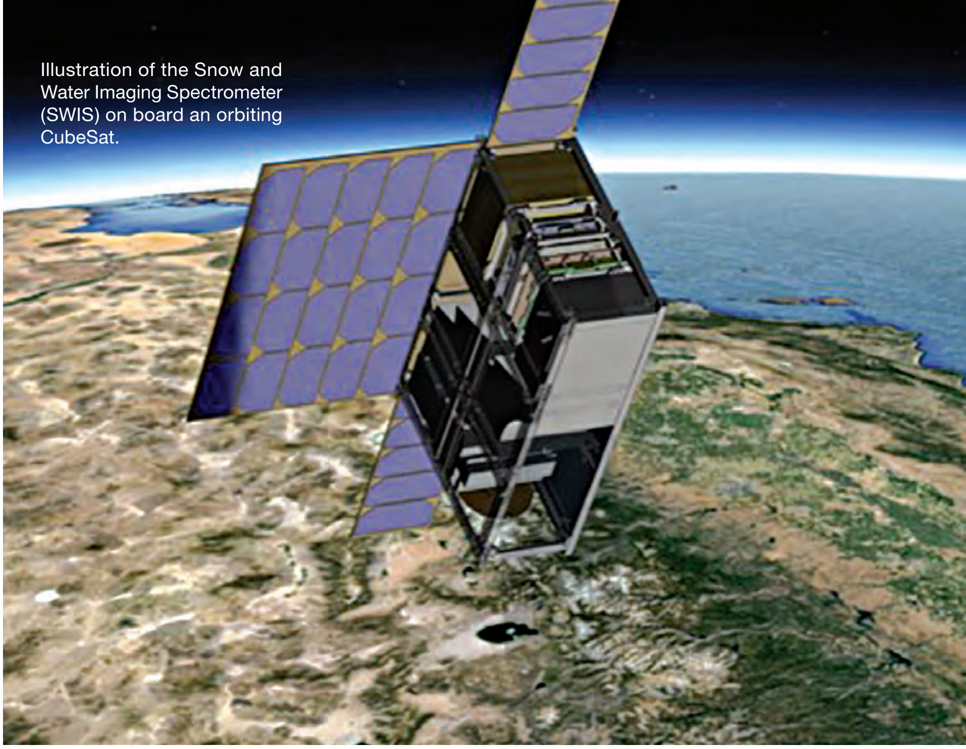
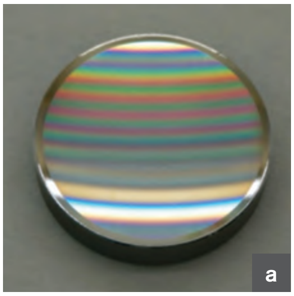
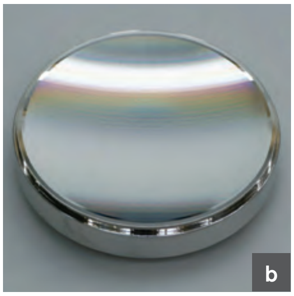


Illustration of the Snow and Water Imaging Spectrometer (SWIS) on board an orbiting CubeSat.





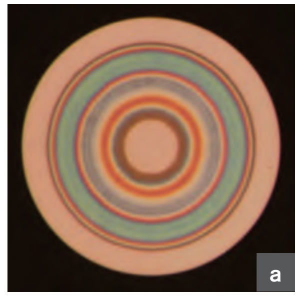
a E-beam-fabricated concave grating for the Snow and Water Imaging Spectrometer (SWIS). Grating is 41 mm diameter, has center-to-edge depth of 2 mm, and shaped grooves to produce tailored efficiency and minimum polarization sensitivity for wavelength range of 350 nm to 1700 nm. **b** E-beam-fabricated concave grating for prototype wide-swath imaging spectrometer. Grating is 122 mm diameter, has center-to-edge depth of 6.2 mm, and shaped grooves to produce tailored efficiency for wavelength range of 380 nm to 2500 nm.

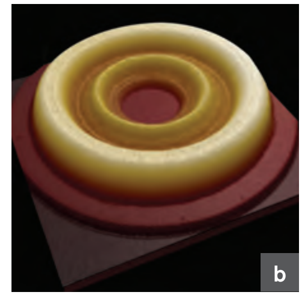
DIFFRACTION GRATINGS FOR CUBESAT SPECTROMETERS

JPL'S IMAGING SPECTROMETER INSTRUMENTS are being developed to attack the most challenging Earth remote sensing applications. Coastal environments exhibit complex spectral signatures with high spatial and temporal variability, and thus they require hyperspectral instruments with high signal-to-noise ratio (SNR), high resolution, and frequent reimaging. JPL's Snow and Water Imaging Spectrometer (SWIS) is designed to achieve these performance requirements from a CubeSat platform. SWIS utilizes a Dyson-type spectrometer design with a concave e-beam-fabricated concave grating (a). The grating is designed with shaped grooves that optimize instrument SNR and minimize polarization sensitivity over the entire 350 nm to 1700 nm spectral range. A fully implemented SWIS system could achieve daily coverage of any point on the globe using 6 CubeSats.

DIFFRACTION GRATINGS FOR WIDE FIELD-OF-VIEW SPECTROMETERS

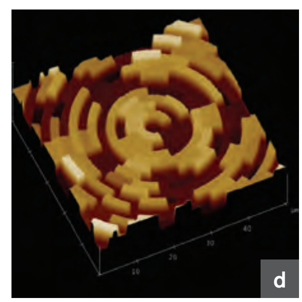
IMAGING SPECTROMETERS with wide field-of-view coverage are desirable as future Landsat instruments. They would provide the enhanced science potential of full simultaneous spectroscopic capability as opposed to the nine non-simultaneous spectral bands of the current Operational Land Imager on Landsat 8. JPL has designed a Dyson-type spectrometer that meets the Landsat requirements of swath, resolution, spectral range, and signal-to-noise ratio. The design requires a large concave grating to achieve high-performance wide-swath spectral imaging. A prototype concave grating meeting similar requirements has been e-beam fabricated at MDL (b). The grating area is 122 mm diameter with 6.2 mm of center-to-edge concave depth—the largest and deepest ever fabricated at JPL. The grooves are precisely shaped to produce a first-order diffraction efficiency spectrum that optimizes the instrument SNR over the required 380 nm to 2500 nm solar reflected wavelength range. The Landsat spectrometer design was shown to meet requirements even in a simulation including stray light ghosts from all shaped-groove grating orders and other spectrometer surfaces.





CORONAGRAPH OCCULTING MASKS FOR THE WFIRST MISSION

JPL IS DEVELOPING CORONAGRAPH TECHNOLOGY to enable direct imaging and spectroscopy of exoplanets using the Coronagraph Instrument (CGI) on the NASA Wide-Field Infrared Survey Telescope (WFIRST) mission. The MDL e-beam group is utilizing its unique capabilities in grayscale electron-beam lithography to fabricate two new types of starlight occulting masks, one for the hybrid-Lyot coronagraph (HLC) design, and another for the phase-induced amplitude apodization complex mask coronagraph (PIAACMC) backup design. The HLC mask is a circular metal spot with a precisely aligned grayscale e-beam-profiled dielectric pattern on top. The PIAACMC mask is an array of circular sections with precisely designed grayscale depths. Both types of masks work in conjunction with the rest of their respective coronagraph optics to suppress the light of a star by nearly nine orders of magnitude; this enables direct imaging and spectroscopy of the star's exoplanets and debris disk. After an initial process development phase, we successfully fabricated, precisely characterized, and delivered prototypes of both types of masks to the JPL coronagraph teams for optical performance evaluation. The masks were used successfully to meet the requirements of NASA progress milestones.



a b Microscope photo and atomic force microscope surface profile of an e-beam-fabricated occulting mask for the WFIRST hybrid-Lyot coronagraph (HLC). c d Microscope photo and atomic force microscope surface profile of an e-beam-fabricated occulting mask for the phase-induced amplitude apodization complex mask coronagraph (PIAACMC).

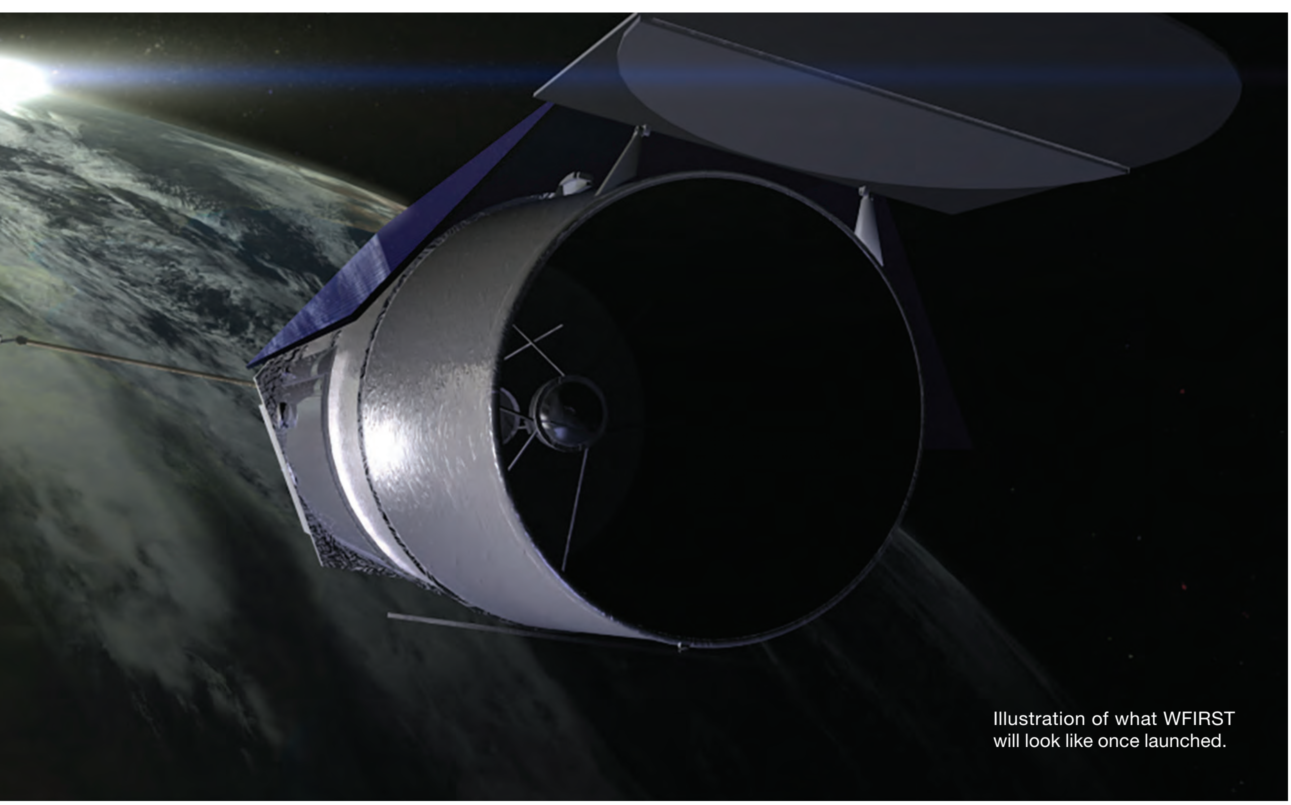


Illustration of what WFIRST will look like once launched.

ADVANCED DETECTORS, SYSTEMS & NANOSCIENCE

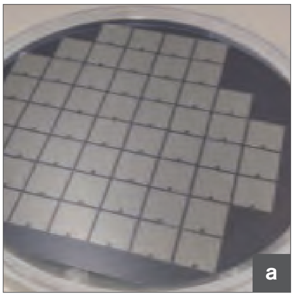
Our group is dedicated to furthering the capabilities of UV/optical/NIR instrumentation and putting MDL technologies to widespread use.

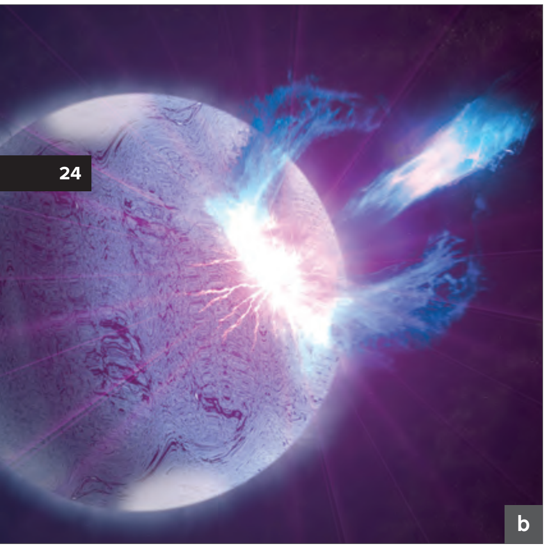
HIGH-PERFORMANCE DEVICES

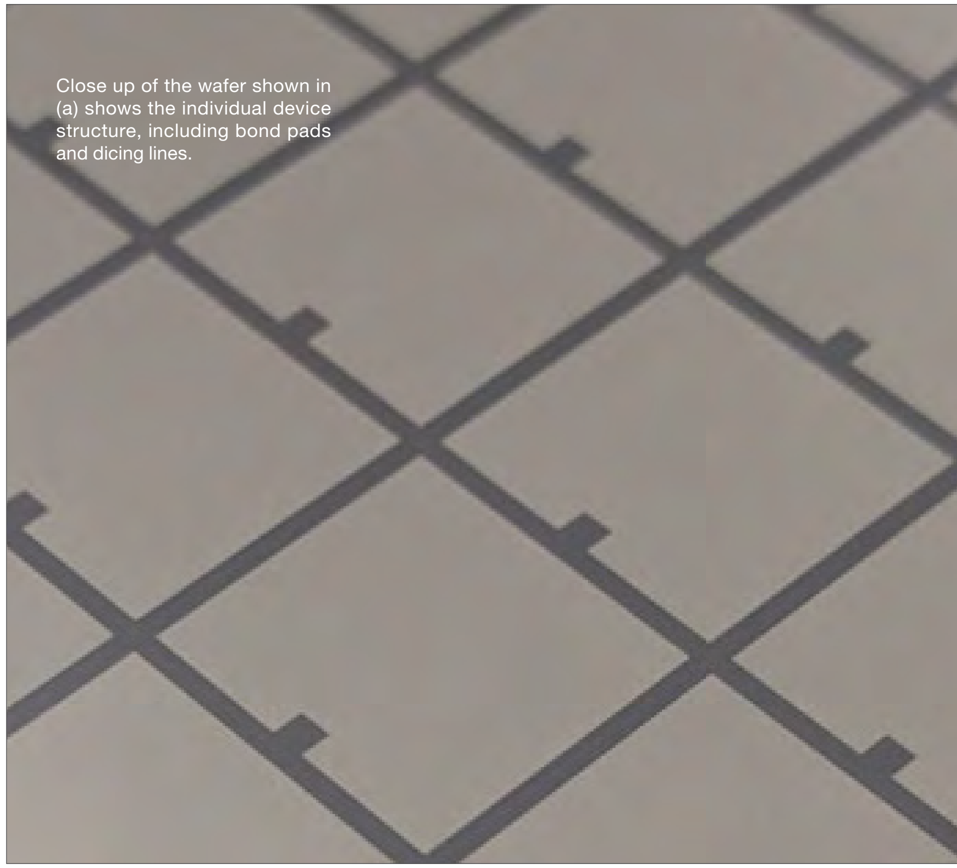
In 2016, NASA selected Large Ultraviolet Optical IR Surveyor Mission (LUVOIR) **and Habitable Exoplanet imager (HabEx)** as two of the four mission concepts for further studies in preparation for the next decadal survey to be conducted by the National Research Council. Both LUVOIR and HabEx will require unprecedented large apertures, high throughput, and wide spectral range. High-reflectivity coatings for mirrors and high-performance detectors are of critical importance. The Advanced Detectors, Systems, and Nanoscience Group has been preparing for these challenges. By the mid 2000s, it had become clear that astrophysics instruments requirements are trending toward larger focal plane arrays (FPAs). Additionally, CMOS and CCD industries had moved to larger-diameter wafers. These factors dictated the need for an equipment upgrade at MDL. Professor Jonas Zmuidzinas, JPL Chief Technologist and then MDL Director, advised the team leader, Shouleh Nikzad, to organize a meeting to hear all of the programmatic and technical pro and con arguments to determine if there was a case for such an investment.

ADVANCES GENERATED AT MDL WILL EXTEND OUR VISION TO UNPRECEDENTED SENSITIVITY OF LOW LIGHT LEVELS THAT WILL ENABLE UNIMAGINED FUTURE DISCOVERIES AND POSSIBILITIES.

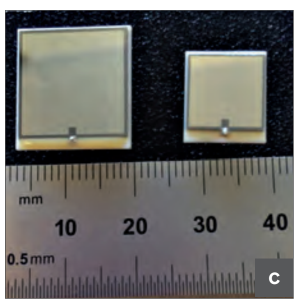
Jonas' advice turned out to be an excellent first step into acquiring the first of its kind 8-inch-diameter wafer capacity silicon molecular-beam epitaxy (MBE). State-of-the-art equipment can help turn good ideas into great products and capabilities. Using this MBE and MDL's atomic layer deposition (ALD), we have produced high performance deep UV, FUV, and UV/Vis/NIR detectors, and a multitude of visible formats in CMOS, CCD, and avalanche photodiode architectures. We have turned a once small R&D effort into a high-throughput end-to-end post-fabrication processing that can be used for delivering high-performance detectors for large FPAs. Young researchers working with our group are supported to continue their work with fellowships from NASA and other agencies; most notable was a Nancy Grace Roman Fellowship to Dr. Erika Hamden. We have had breakthroughs in developing solar-blind silicon detectors, ultra-stable deep UV detectors, and novel UV imaging spectrometers. MDL detectors are used in synchrotrons, in semiconductor fabrication, in sounding rockets, at Palomar Observatory and at Kitt Peak Observatory, and are slated for balloons and are baselined for satellite missions. Spinoff developments have led to producing high-reflectivity UV mirror and grating coatings. All these efforts prepare us for the challenges to come.







Close up of the wafer shown in (a) shows the individual device structure, including bond pads and dicing lines.

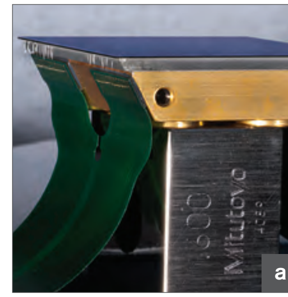


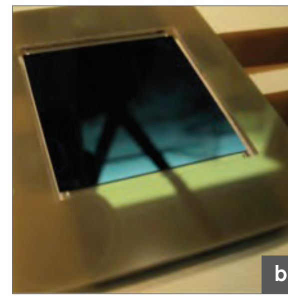
ULTRA-STABLE, HIGH-EFFICIENCY DUV DETECTORS

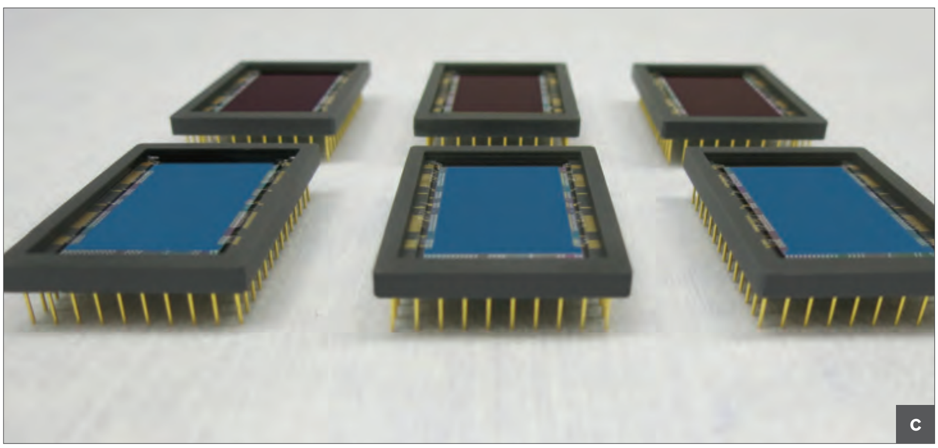
THE UV SENSITIZATION of silicon-based detectors can be achieved through a variety of techniques, including ion implantation or by coating the detector surface with a phosphorescent material (e.g., lumogen) that converts UV photons to visible photons. JPL's approach is based on the use of molecular-beam epitaxy (MBE) to achieve two-dimensional doping for surface passivation. MDL's Michael Hoenk is the co-inventor of delta-doped (1992) and inventor of the superlattice-doped (2013) detector arrays. These processes have been demonstrated on a variety of silicon-based detector formats, resulting in 100% internal quantum efficiency (QE) throughout the UV-visible wavelength ranges, as well as record-breaking stability against potentially damaging radiation. Originally an industry-sponsored effort, superlattice doping has been recognized by other funding agencies (including DOE, NASA, and industry) as a transformative technology development. Currently Hoenk is working to develop gamma-ray scintillator technology with sub-nanosecond temporal resolution and the capability to withstand unprecedented rates and doses of high-energy gamma radiation. The system consists of doped BaF2 scintillating crystals and solar-blind silicon avalanche photodiodes (APDs) for detecting the fast scintillation component of BaF2. High efficiency and fast response are achieved by using MBE to grow a doping superlattice on the avalanche photodiode. Integrated solar-blind antireflection coatings enable efficient detection of the fast BaF2 scintillation at 220 nm, with strong suppression of the slow BaF2 scintillation at 330 nm. These coatings are based on metal dielectric filters (MDFs) formed by combination of atomic layer deposition (ALD) and metal evaporation. The ongoing effort is a collaboration with Caltech and Radiation Monitoring Devices Inc. with DOE funding; however, the ultrafast response time of these detectors is ideal for NASA applications such as x-ray pulsar navigation, time-gated Raman spectroscopy, and planetary gamma ray spectrometers.

END-TO-END POST-FABRICATION PROCESSING

THE ADVANCED DETECTORS, SYSTEMS & NANOSCIENCE GROUP has developed an end-to-end processing of fully-fabricated wafers to produce high-performance silicon detectors. Our processes include wafer-scale thinning, two-dimensional doping, and custom coatings. Todd Jones' creative approach has contributed to many aspects of the group's capability from high-precision thinning to custom packing. Jones' initial work was in frame thinning Cassini CCD spares as part of UV and low-energy particle detector development. Since that time, Jones has devised post-fab thinning techniques that work for a variety of device architectures, for both frame-thinned and supported devices. Recently, he has developed a custom packaging and wire-bonding scheme for closely-butted mosaic focal plane arrays. Detectors packaged using these techniques were delivered to Caltech Optical Observatories for the WaSP and ZTF. The completed devices exhibit <1 µm peak-to-valley height variation, greatly outperforming the industry standard.

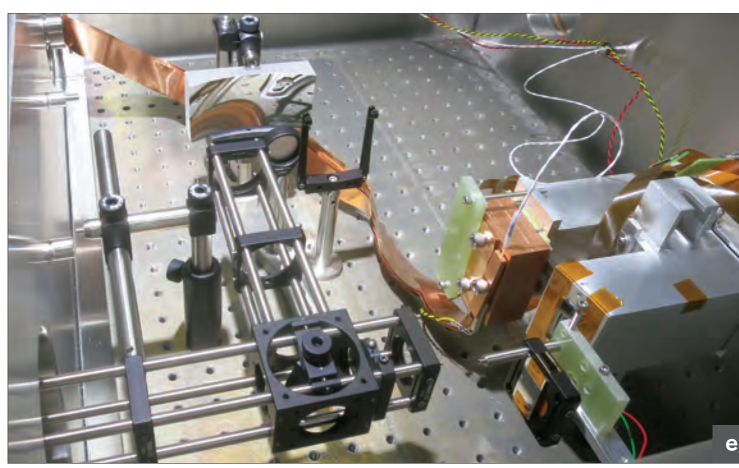






The post-fabrication processing steps can be applied to a variety of silicon-based detector platforms. **a** Superlattice-doped and antireflection-coated 4-megapixel CCD (STA, Inc.) in custom packaging developed for integration at Palomar through a collaboration with Caltech Optical Observatories. **b** The same device shown in (a) in custom packaging developed for a low-profile camera configuration. **c** Several superlattice-doped and antireflection-coated 2-megapixel electron-multiplying CCDs (e2v Inc.). **d** Dr. Jones' expertise in wafer thinning and device packaging results in uniform, controllable and repeatable device response. **e** Photograph of the UVS testbed with both the FUV and NUV channels installed.

left a Photograph showing wafer-scale patterning of the fully processed device wafer. **b** Gamma-ray bursts from neutron stars, shown here in an artist's rendering, provide information on the dynamics of the star's surface, providing new insights into what lies beneath. **c** Two packaged superlattice-doped, solar-blind APDs ready for testing. Both were fully processed at wafer level prior to dicing and packaging. The 14 mm x 14 mm device format is shown on the left and a 9 mm x 9 mm device is on the right. **d** John Hennessy is developing solar-blind, UV filters using ALD and other deposition techniques. **e** Dr. Hoenk, the JPL PI on this work, is an inventor of delta and superlattice-doped silicon arrays.



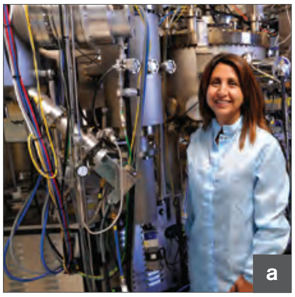
ULTRAVIOLET SPECTROMETER BASED ON MDL TECHNOLOGIES

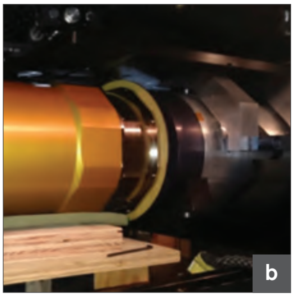
WE ARE DEVELOPING a state-of-the-art, compact ultraviolet spectrometer (UVS). Advanced components based on MDL technologies comprise the UVS, including UV-enhanced EMCCDs, high-efficiency reflective UV optics with ultra-thin protective coatings, and e-beam fabricated gratings. The UVS features a two-channel design, spanning the near-UV wavelength range (250-600), and the far UV extending to a challenging spectral range (100-250 nm).

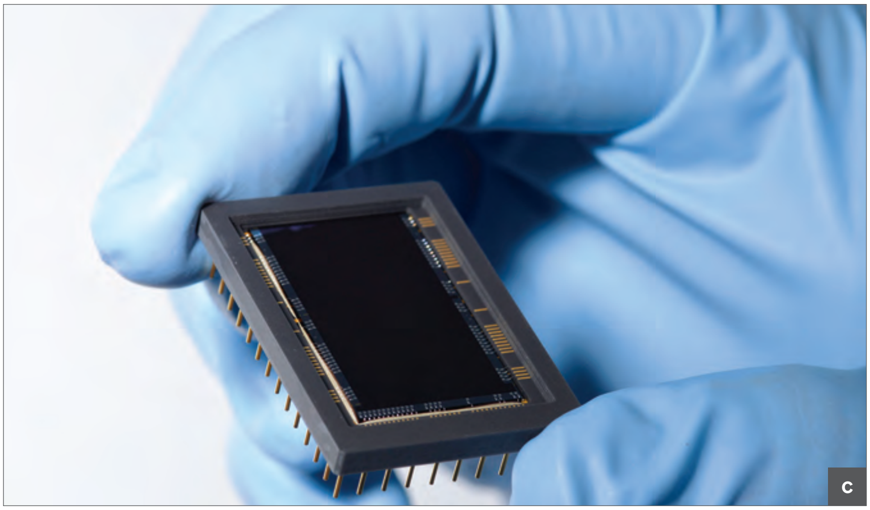
FROM THE LABORATORY TO OUTER SPACE

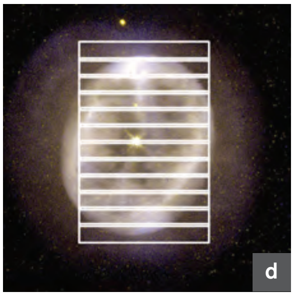
SHOULEH NIKZAD, a Senior Research Scientist and the technical group supervisor for the Advanced Detectors, Systems and Nanoscience Group, has been leading innovation, development, advancement, and deployment of delta- and superlattice-doped devices into a multitude of science missions and instruments. She also initiated and invented detectors for low-energy particle detection with new records in low-energy detection threshold, as well as solar-blind detectors with low operating voltages. She has formed national and international collaborations that help expansion in various applications, and has led detector deliveries to multiple sounding rockets. Currently, a balloon flight and another sounding rocket are slated to use two different types of detectors produced by the group for astrophysics and cosmology studies. During 2015, these customized UV detectors were used for ground-based on-sky observations in preparation for these upcoming balloon and rocket flights. The balloon-borne experiment, the Faint Intergalactic Red-shifted Emission Balloon experiment (**FIREBall-2**) uses a spectrograph to map emission from the intergalactic and circumgalactic mediums. FIREBall-2 will use a superlattice-doped and antireflection coated electron multiplying EMCCD (e2v, Inc.) optimized for the stratospheric balloon window spanning 200-225 nm. In late 2015, the flight prototype was used for on-sky observations from Palomar Observatory, demonstrating both UV sensitivity and signal amplification required for this mission.

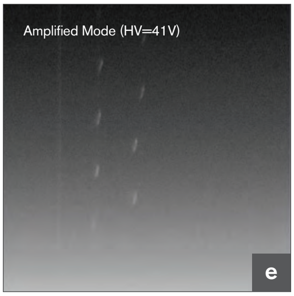
Development of the FIREBall-2 detector is a collaboration with the California Institute of Technology (PI, Chris Martin), e2v, and Columbia University. The Colorado High-resolution Echelle Stellar Spectrograph (**CHESS**) is a rocket-borne instrument designed for photon-limited sensitivity in the 100-160 nm bandpass; CHESS will use a 12-megapixel superlattice-doped p-channel CCD developed by Lawrence Berkeley National Laboratory (LBNL) for a dark-energy mission. Recently, the flight prototype payload was installed on the telescope at Mount Bigelow for on-sky calibration, successfully demonstrating detector operation and UV sensitivity. Development of the CHESS detector system is a collaboration with the University of Colorado at Boulder (PI, Kevin France), LBNL, and Arizona State University.



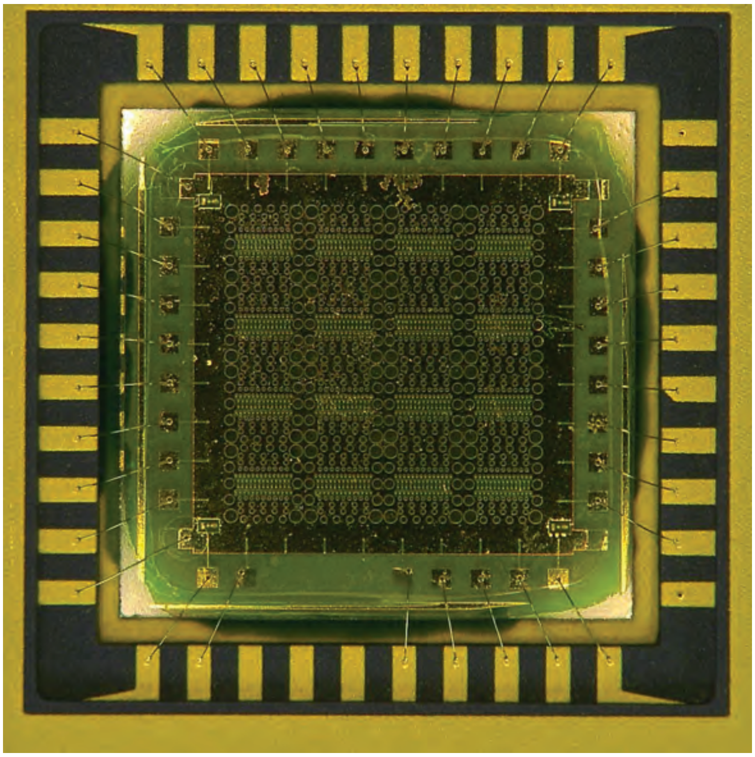




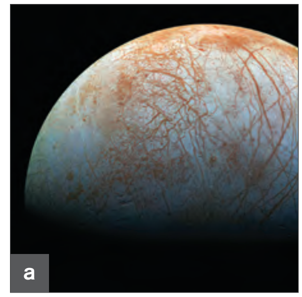


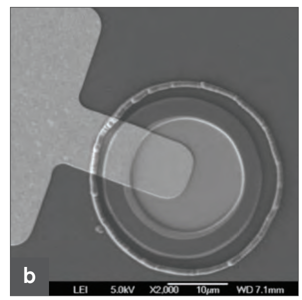


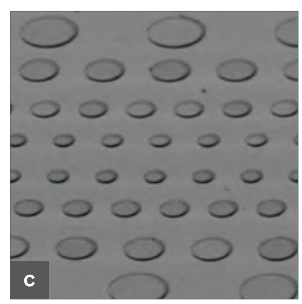
First test of a delta-doped EMCCD on Palomar using the Cosmic Web Imager (CWI) spectrograph. **a** Dr. Shouleh Nikzad standing in front of the 8-inch wafer Molecular Beam Epitaxy (MBE) machine, inspecting a CHESS detector prototype that has been UV sensitized by bandstructure engineering using the MBE. **b** Photograph of the FIREBall dewar (gold) attached to the Norris camera on CWI (gray/black). **c** This work uses a superlattice-doped and AR-coated EMCCD optimized for the stratospheric balloon window spanning 200-225 nm. **d-f** Images of the NGC 2022 (planetary nebula) observed at H-β with the delta-doped EMCCD. **e** An amplified image with the H-β spectral line clearly visible in several slices. **f** The same field of view and exposure time as shown in d, but without amplification. The H-β spectral line is not visible.

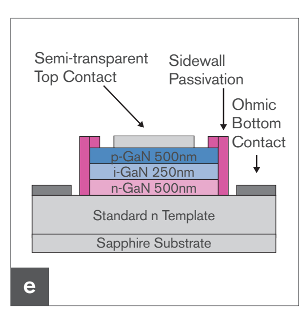


left. Photograph of a packaged device comprising an array of GaN APDs of various sizes spanning 25-500 mm.









DEVICES BASED ON WIDE-BANDGAP MATERIALS

THE III-NITRIDE MATERIAL FAMILY can be alloyed to span the group of direct bandgap semiconductors spanning a bandgap range from 3.4 to 6.2 eV. Thus, detectors based on GaN, and related alloys like AlGaN, are inherently blind to visible or solar light, making them ideal for the detection of faint UV signals. However, challenges arise due to the lack of affordable native substrates; and growth on mismatched substrates typically leads to high defect density and high leakage currents in the resulting devices. In spite of these challenges, significant progress has been made in the development of GaN-based photocathodes and avalanche photodiodes (APDs). Our approach is based on the use of novel growth and passivation techniques in order to optimize material quality. We are investigating the use of arrays of vertical, mesa-isolated GaN APDs as UV imaging sensors capable of operating with high gain and with improved radiation tolerance. The current effort is led by Doug Bell, who brings his considerable expertise in device and interface characterization to this development, and is a collaboration with Shouleh Nikzad, SUNY-Polytechnic, and TU Delft, with ongoing support from NASA, where TU Delft brings their own support and provides expertise in design and fabrication of readout integrated circuits for single-photon-counting detection.

a. NASA's planned Europa Mission is designed to provide unprecedented insight into the icy moon's capacity to support life. Devices based on III-N materials being developed in MDL are ideally suited to withstand the harsh radiation environment the spacecraft will encounter. **b.** Scanning electron microscopy (SEM) image of a single-pixel GaN APD mesa structure with electrical contact. **c.** SEM image of an array of GaN APDs of various sizes, spanning 25-100 μm. **d.** Dr. Bell's pioneering work in the field of wide-bandgap materials has led to the development of devices capable of operating at high gain and with improved radiation tolerance. **e.** Schematic showing the APD mesa structure, including the passivated sidewall.

“The Infrared Photonics Technology Group highly appreciates the leadership, guidance, and support provided by **JONAS ZMUIDZINAS** to the Microdevices Laboratory’s infrastructure.”

INFRARED PHOTODETECTORS

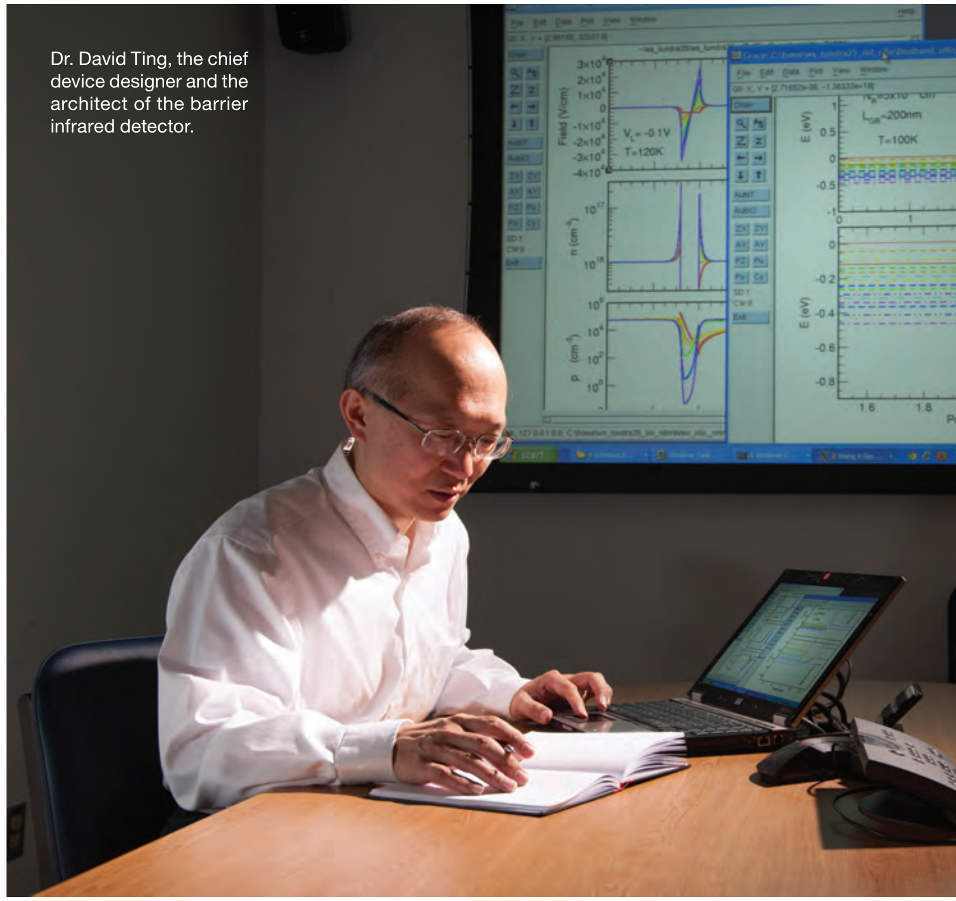
STATE-OF-THE-ART INFRARED DETECTORS

The goal of the Infrared Photonics Technology Group at MDL is to develop novel high-performance III-V compound semiconductor-based infrared detectors and focal plane arrays for NASA and other government agencies, thereby enhancing U.S. competitiveness worldwide. This group has been at the forefront of advance infrared detector technology development and has developed many patentable novel concepts in the past. It is fully capable of performing novel detector designs, epitaxial materials growth, end-to-end large-area detector fabrication process, characterization of infrared focal plane arrays, and delivery of focal planes to infrared instruments.

INNOVATIONS AT MDL ENABLE OBSERVATIONS OF OUR PLANET IN AN INFRARED REGION JUST BEYOND OUR REACH, AS WELL AS MAPPING OF THE WORLD'S ECOSYSTEMS, DEFENSE, CLOUD STRUCTURES, AND NATURAL DISASTERS.

The members of the Infrared Photonics Technology Group have produced over 250 publications and 22 U.S. and international patents on infrared detection technologies. Most of these patents are commercialized via the Caltech/JPL commercialization process. Many infrared detector technologies including the high-operating-temperature barrier infrared detector developed by the Infrared Photonics Technology Group at MDL have been successfully transferred to U.S. industries for applications.

Photo of the Infrared Photonics Technology Group. This group's technical capability extends from basic device modeling based on quantum mechanics to fabrication and demonstration of novel infrared detectors and focal planes that enable new instruments for NASA and DoD missions.



Dr. David Ting, the chief device designer and the architect of the barrier infrared detector.

BARRIER INFRARED DETECTOR

MDL'S INFRARED PHOTONICS TECHNOLOGY GROUP is engaged in the development of novel infrared detectors and single-band/multi-band focal plane arrays for NASA and defense applications. This group has been at the forefront of advanced infrared detector technology development, and has developed many patented novel concepts in the past, including the antimonides superlattice-based, high-operating-temperature (HOT) barrier infrared detectors (BIRD) for space and terrestrial applications. HOT BIRD is a breakthrough infrared detector technology capable of operating at 150 K with spectral coverage of not only the entire mid-wavelength infrared (MWIR) atmospheric transmission window (3 – 5 µm), but also the short-wave infrared (SWIR; 1.4 – 3 µm), and the near-infrared (NIR; 0.75 – 1.4 µm). The recently selected NASA 6U CubeSat Infrared Atmospheric Sounder (CIRAS) is based on JPL-developed MWIR HOT BIRD focal plane array technology.

The mid-wavelength n-type BIRDs can suppress material defects and surface-related dark current while yielding nearly 100% quantum efficiency. However, the quantum efficiency of a longer wavelength infrared (LWIR) BIRD was a concern, having been limited to about 30% due to insufficient diffusion length. This results from increasing vertical (transport) direction carrier effective mass with decreasing superlattice band-gap. Dr. David Ting has designed a novel device architecture where another layer is judiciously incorporated into the BIRD, without significant increase in dark current levels. The novel double-layer technique enhanced the quantum efficiency of LWIR BIRDs to about 80%. This is a breakthrough advance in the LWIR BIRD technology, as well as a very significant breakthrough in state-of-the-art LWIR detector technology, and will enable breakthrough capabilities.

NOVEL INFRARED DETECTORS AND SINGLE-BAND/MULTI-BAND FOCAL PLANE ARRAYS FOR NASA AND DEFENSE APPLICATIONS.

a Artist's rendering of CIRAS CubeSat in a low-Earth orbit. CIRAS is based on a HOT BIRD focal plane array. **b** Members of the Center for Infrared Photodetectors. **c** An infrared image of the group shown in (b).

BIRD FABRICATION PROCESS

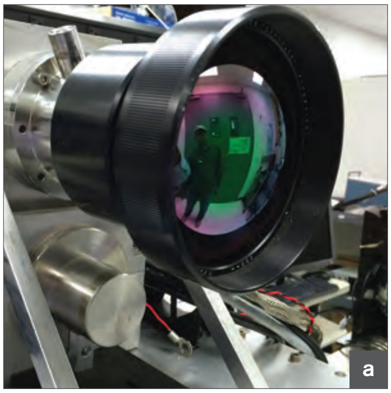
THE ANTIMONIDES-BASED TYPE-II SUPERLATTICES have a great potential in realizing high-performance, large-format, highly-uniform infrared focal plane arrays at lower cost. The availability of large-area, epi-ready GaSb substrates, along with relatively easy III-V materials growth and processing technology compared to its II-VI counterpart, make this possible.

In (b), Dr. Arezou Khoshakhlagh is growing the type-II superlattices materials on 4-inch GaSb substrates using a Veeco Gen-3 molecular-beam epitaxy (MBE) machine in the Microdevices Laboratory. MBE-grown type-II superlattice materials on GaSb substrates always go through a thorough material characterization process (i.e., photoluminescence and minority carrier lifetime measurements, etc.) to evaluate the material quality.

Large-area detector arrays with small pixel pitches (i.e., 10-30 microns) are fabricated by dry etching through the top contact and photosensitive absorber superlattice, into the detector common layer. The dry etching is done using an inductively coupled plasma (ICP) dry etching system using a combination of chlorine and other gases.

Last year, the Microdevices laboratory acquired a PlasmaTherm hot-wall deep dry etching system shown in image (c). The image below shows Mr. Sam Keo loading a partially processed 4-inch GaSb wafer into the PlasmaTherm dry etching system. Ohmic contact metal is evaporated and unwanted metal is removed using a metal lift-off process. Typically, nine megapixel detector arrays can be processed on a 4-inch GaSb wafer with etch rate uniformity better than 1% across the array. Indium bumps are then evaporated on top of the detectors for hybridization with ROICs. Image (d) shows a processed wafer with many ¼ VGA format detector arrays.

a. A megapixel mid-wave/long-wave dual-band QWIP camera. b. Dr. Arezou Khoshakhlagh using a Veeco Gen-3 molecular beam epitaxy machine. c. Newly installed PlasmaTherm inductively coupled plasma hot-wall deep dry etching system. d. A processed wafer with many VGA format detector arrays.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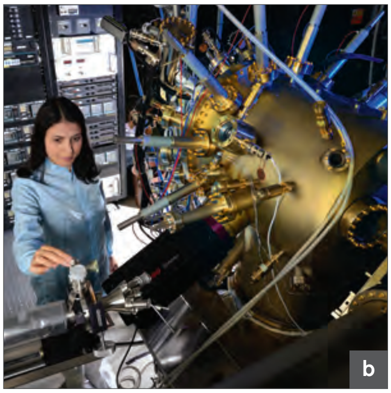
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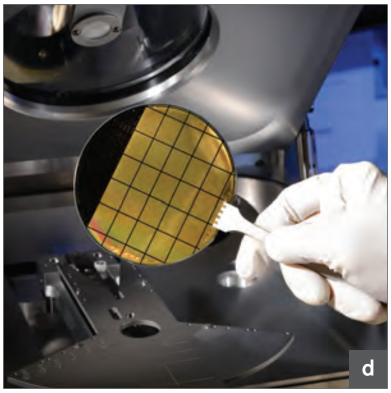
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This image shows the lead process development engineer Mr. Sam Keo loading a 4-inch GaSb wafer into the PlasmaTherm inductively coupled plasma hot-wall deep dry etching system.

"PROF. JONAS ZMUIDZINAS helped lay the foundation of the Superconducting Materials and Devices Group and continues to be a source of ideas for truly novel technologies over nearly three decades."

SUPERCONDUCTING MATERIALS & DEVICES

For nearly three decades, the Superconducting Materials and Devices Group has been developing novel superconducting, and related non-superconducting, technologies for application to areas as diverse as astrophysics, planetary science, quantum computing, and optical communications.

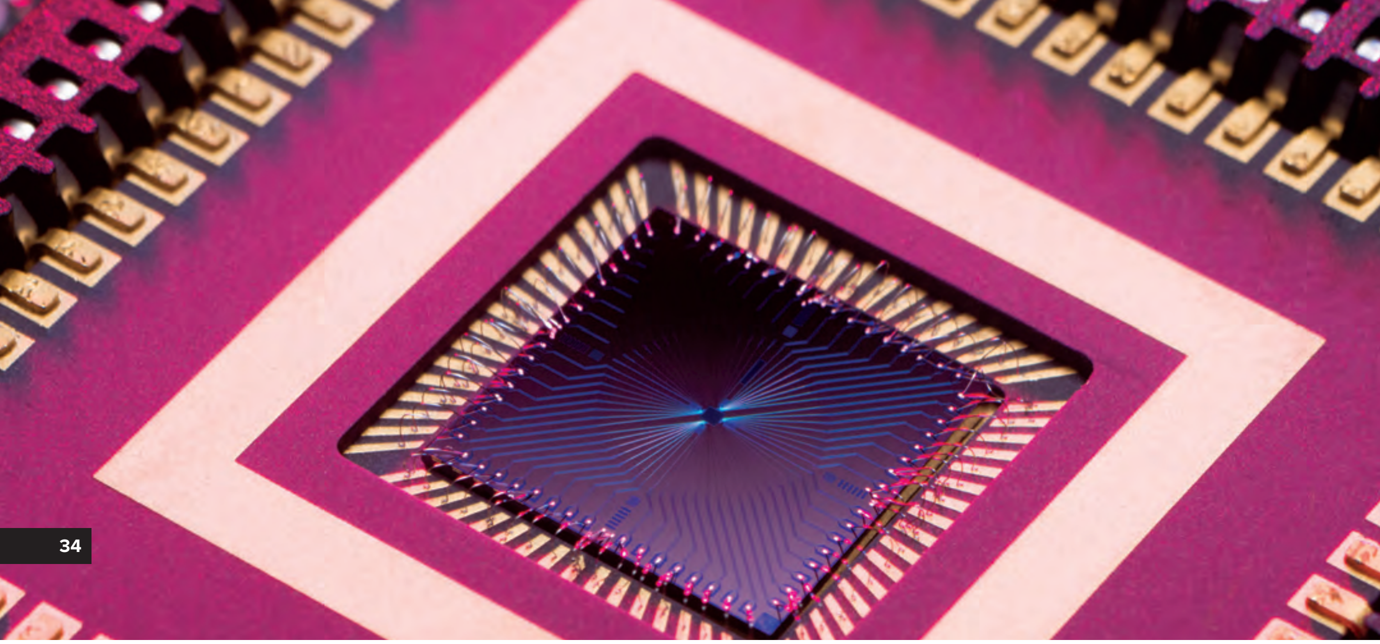
NOVEL TECHNOLOGIES

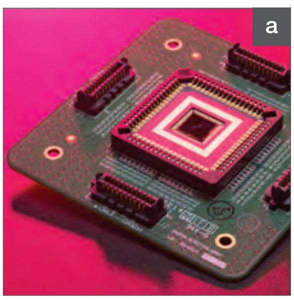
The superconducting detector effort started in the mid-1980s as a JPL/Caltech joint venture to produce high-frequency superconductor-insulator-superconductor (SIS) mixers. Caltech Professor Thomas Phillips had done pioneering SIS mixer development at AT&T Bell Laboratories before coming to Caltech and wanted to transfer the technology. He enlisted researchers at JPL to pursue the device side of the venture. While the groundwork for SIS mixer development occurred in these pre-MDL years, the opening of MDL in 1989 and the arrival of Professor Jonas Zmuidzinas in that same year was the spark that accelerated development and allowed for expansion into other detector technologies. Both Professor Phillips' and Professor Zmuidzinas' long-term interest was in developing mixers for a space mission. Professor Phillips, as director of the Caltech Submillimeter Observatory (CSO), a radio telescope in Hawaii, had little time for the day-to-day development of the technology. Professor Zmuidzinas took on that role and spearheaded the advanced development of SIS mixers, pushing both performance and high-frequency operation in addition to vetting the technology on NASA's Kuiper Airborne Observatory (KAO). This intimate involvement in development in the JPL superconducting detector technology eventually led to JPL/NASA's involvement in the highest frequency SIS heterodyne receiver on the Herschel Space Observatory (HSO).

As the SIS technology approached space readiness, the original work on superconducting mixers has spawned new areas of development and new capabilities, ranging from quantum computing to optical communication. The microwave kinetic inductance detector (MKID), invented at Caltech/JPL by Professor Zmuidzinas in collaboration with key group members Rick LeDuc and Peter Day, has been adopted worldwide as the next important step in producing larger, more sensitive detector arrays used for key scientific investigations. These include the ability to peer deeper into the atmospheres of the giant outer planets and their moons, to survey star-forming regions, to study the very first stars, to look for dark matter, and to map the edge of the universe.

The most recent developments, the parametric amplifier (paramp) and the kinetic inductance parametric up-converter (KPUP), have left conference audiences stunned to silence at the novelty and speed at which these new concepts are formulated and demonstrated. At the heart of all of this good work is a group of people, like Professor Zmuidzinas, who are just plain curious and want to harness new ideas.

JPL HAS BEEN A PIONEER IN THE DEVELOPMENT OF SUPERCONDUCTING DETECTORS FOR FAR-INFRARED AND SUBMILLIMETER ASTROPHYSICS FOR 25 YEARS.



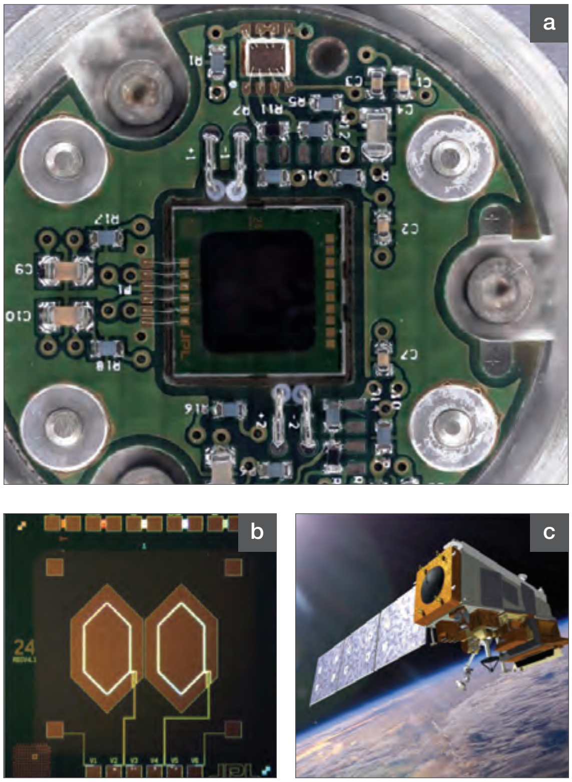


Top A 64-pixel 320-micron diameter SNSPD array under development for a future ground terminal for NASA's Deep Space Optical Communication (DSOC) project. **a** A 64-pixel 320-micron-diameter SNSPD array under development for a future ground terminal for NASA's Deep Space Optical Communication (DSOC) project, mounted in a chip carrier and cryogenic circuit board. The devices are designed, fabricated, and tested at JPL. **b** The 5-meter Hale telescope at Palomar Observatory, which will be used as a ground terminal in NASA's upcoming Deep Space Optical Communication technology demonstration mission.

SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTORS FOR OPTICAL COMMUNICATION AND QUANTUM OPTICS

SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTORS (SNSPD) are the highest performance single-photon-counting detectors available in the infrared. Under development at MDL since 2005 for applications in optical communication and quantum optics, JPL SNSPDs have shattered records for detection efficiency, active area, and array pixel count. In 2012, JPL and NIST developed fiber-coupled WSi SNSPDs with record-breaking 93% system detection efficiency at 1550 nm, and used these detectors in a proof-of-concept optical communication experiment to encode 13 bits of data in every photon. In 2013, JPL developed 12-pixel fiber-coupled SNSPD arrays and successfully infused them into a ground terminal for the Lunar Laser Communication Demonstration, the first bidirectional laser communication experiment from beyond Earth's orbit. Following the success of this experiment, NASA has moved forward with the Deep Space Optical Communication (DSOC) project, which will be the first true test of optical communication technology from deep space. Planned to launch with the next Discovery mission, DSOC features a JPL-built flight transmitter and a ground receiver based on an ambitious MDL-fabricated WSi SNSPD array. This 64-pixel device has over 300 times the active area of the record-breaking single-pixel SNSPD developed at MDL in 2012, and will count single photons at rates approaching 1 gigacount per second. This detector will be the centerpiece of a cryogenic ground terminal instrument for DSOC using the 5-meter Hale telescope at Palomar Observatory in 2021.

JPL's SNSPD development program has also provided extensive support to the quantum optics community, enabling a variety of fundamental physics experiments. In 2015, MDL-fabricated SNSPDs were used in a loophole-free test of Bell inequalities at NIST, the first-ever observation of single-phonon dynamics in a nanoscale optomechanical system at Caltech, and in high photon-efficiency quantum communication experiments at MIT. The SNSPD team is currently providing support to an effort to develop a quantum communication demonstration from the International Space Station, and has developed photolithographic SNSPD arrays for a DARPA quantum key distribution program. In collaboration with NIST and Temple University, MDL engineers are developing high-operating-temperature SNSPDs based on magnesium diboride and molybdenum silicide, ultraviolet SNSPDs optimized for quantum computing applications, waveguide SNSPDs for integrated photonics, and commercializable SNSPD arrays with an industry partner.



FOCAL PLANE MODULE FOR RADIATION BUDGET INSTRUMENT (RBI)

MDL IS BUILDING THE FOCAL PLANE MODULE for the Radiation Budget Instrument (RBI)(a). RBI is a NASA climate experiment that measures the effect of clouds on Earth's energy balance. Additionally, RBI allows scientists to understand the connection between Earth's incoming and outgoing energy. RBI will fly on the Joint Polar Satellite System 2 (JPSS-2) mission planned for launch in November 2021 (c).

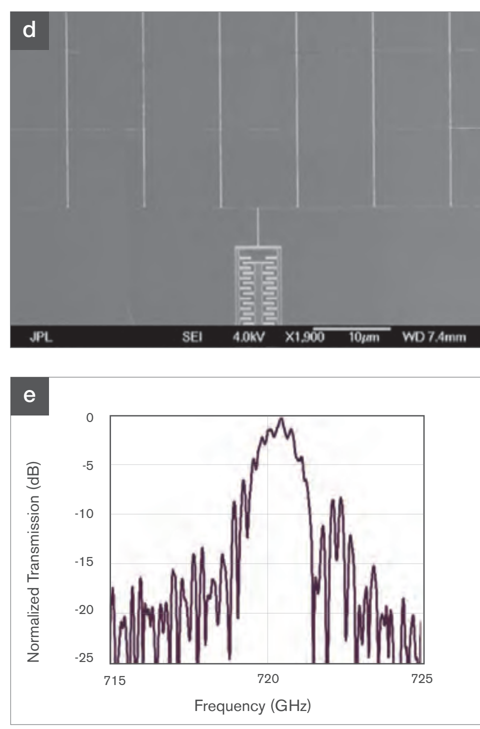
At the heart of the focal plane module is the custom thermopile chip (b). The thermopile chip is a 7 x 7 mm^2 silicon-on-oxide die roughly 500 µm thick. On each die are two pixels roughly 1.9 mm^2 in size where each pixel consists of a thin (100 nm), suspended low-stress silicon nitride (LSN) membrane; spanning the perimeter of the LSN membrane are roughly 1000 Bi-Sb-Te thermocouples. Each thermocouple consists of a 'hot' junction thermally anchored to the suspended membrane and a 'cold' junction, heat sunk to the substrate. An optical coating called "gold black" is deposited on top of the chip, making the pixel sensitive to incoming radiation from the UV through the far-IR.

a. Close-up of the focal plane module (FPM) for RBI. The detector chip is mounted to a baseplate and wire bonded to a circuit board with passive elements and active components. b. Optical image of thermopile detector without optical coating. c. RBI will fly on the Joint Polar Satellite System 2 (JPSS-2) mission planned for launch in November 2021. NASA awarded Harris Corporation a contract to provide RBI; Harris has partnered with JPL to build the focal plane module, which is an enabling technology for the entire mission.

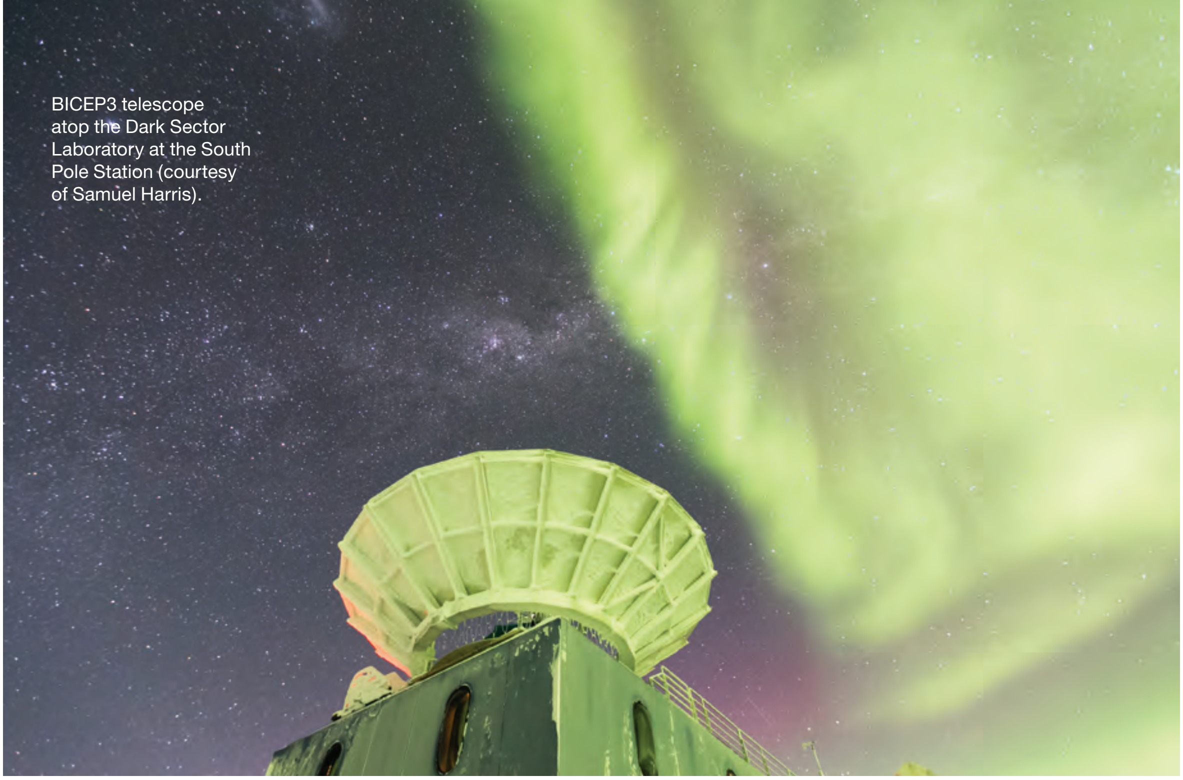
SCIENTISTS CONTINUE THE DEVELOPMENT OF DEVICES THAT DETECT THE COSMIC MICROWAVE BACKGROUND AND THE ELEMENTAL COMPOSITION OF DISTANT GALAXIES DURING THE FORMATION OF THE UNIVERSE AND EMPOWER OUR NEW TELESCOPES.

IMMERSION GRATING SPECTROMETER WITH QUANTUM CAPACITANCE DETECTOR READOUT

DEVELOPMENT CONTINUES ON THE QUANTUM CAPACITANCE DETECTOR with the objective of developing a wafer-level spectro-meter with moderate (R=600) spectral resolution and photon-shot-noise-limited performance. The quantum capacitance detector (QCD) is now mature, consistently yielding $10^{-20}W/Hz^{1/2}$ noise equivalent power with end-to-end efficiency of the order of 60%. A new type of QCD with a wire mesh absorber has shown shot-noise limited performance of four orders of magnitude in optical signal power. The mesh absorber opens up new opportunities for the QCD, as it couples efficiently to multi-mode instrumentation such as is often used with far-IR cameras and spectrometers. In particular, a mesh absorber works well for coupling to the THz / far-IR waveguide grating spectrometer we are developing. The spectrometer is micro machined from a single 4-inch silicon wafer. A device covering 550 to 980 GHz and providing a resolving power over 600 across this full band was already demonstrated. The use of silicon as a propagation medium makes this new spectrometer a factor of ~ 3 smaller in all dimensions, and a factor of at least 100 lower mass than a comparable free-space device. This palm-sized device offers new opportunities for spaceborne far-IR spectroscopy of the earliest galaxies and our home planet.



d. Mesh absorber QCD consisting of 100-nm wide aluminum wires in a 10-µm unit cell grid. Also shown is the gate capacitor used to bias the single-Cooper-pair box island, which is the vertical wire connecting the capacitor to the bottom of the wire mesh. e. Transmission between input feed and 720-GHz output port of a silicon spectrometer showing a spectral resolution R~600.

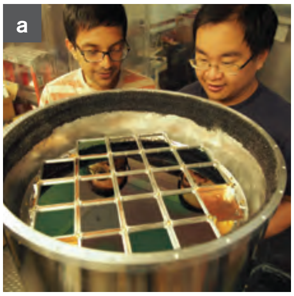


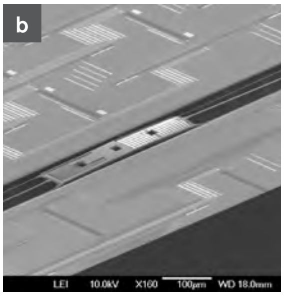
BICEP3 telescope atop the Dark Sector Laboratory at the South Pole Station (courtesy of Samuel Harris).

COSMIC MICROWAVE BACKGROUND MEASUREMENTS

THE POSSIBLE DETECTION of primordial gravitational waves in the cosmic microwave background (CMB) by BICEP2 is one of the most exciting scientific advancements of the decade. These waves should have imprinted a faint swirling "B-mode" pattern in the CMB's polarization and, if confirmed, would tell scientists what happened in our universe in the first trillionth of a trillionth of a trillionth of a second after the big bang. They would probe the laws of physics at the highest conceivable temperatures where the fundamental forces should unify and where effects of quantum gravity are important.

While data from the Planck satellite suggest that at least half of BICEP2's original detection likely came from glowing dust within our galaxy, many teams are racing to perform follow-up measurements at other frequencies to better control for these foregrounds and test if the remainder of BICEP's detection was from the big bang. The BICEP team has installed five additional BICEP2-style cameras into the Keck Array at the South Pole. Since 2014, they have been observing with these at both 150 GHz and 90 GHz channels, publishing the initial results from those surveys in January 2016 in *Physical Review Letters* and placing the tightest constraints yet on inflationary gravitational waves. More recently, the team has completed the installation of the much larger BICEP3 camera, which is the equivalent of all five Keck Array cameras, mapping exclusively at 90 GHz. This has freed up four of the five Keck cameras to map at a third band: 230 GHz.





a. BICEP3 focal plane prior to installation (courtesy of Zeeshan Ahmed). **b.** JPL/MDL antenna array-coupled TES bolometer. Infrared (IR) radiation is coupled from the slot antenna through a micro-strip binary tree (top left of the micrograph) to a free-standing silicon nitride island (center of the micrograph). The IR is converted to heat by a resistor on the island and the temperature change is monitored by the TES, also on the island (courtesy of Anthony Turner).

The SPIDER team flew six BICEP-style cameras in a long-duration, high-altitude balloon flight over Antarctica in January 2016 and is actively analyzing the data. SPIDER is the most sensitive instrument to date to observe the CMB. Their first flight covered 150-GHz and 90-GHz observing bands, and MDL scientists are currently developing 280-GHz detectors for a second flight, anticipated in 2018.

The key technology driving this science is JPL/MDL's antenna array-coupled transition-edge sensor (TES) bolometers. The technology is entirely printable and easily adjusted in fabrication to receive different spectral channels — two features that have provided the BICEP team the flexibility to keep ahead of their competition. They will continue using this detector technology with the BICEP Array — four copies of the larger BICEP3 camera — to begin deployment in 2019, which will add new frequency channels (40 GHz and 280 GHz) and expand the number of detectors by another factor of 10 beyond the existing instruments.

YBCO KINETIC INDUCTANCE BOLOMETERS

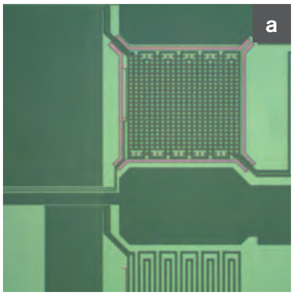
IN A NOVEL APPLICATION, kinetic inductance bolometers (KIBs), suspended on silicon nitride membranes, are fabricated using the high-temperature superconductor Yttrium Barium Copper Oxide (YBCO). These KIBs, invented at MDL, are being developed for use in planetary science missions. They offer a higher operating temperature than conventional superconducting detectors. Passively cooled to 55 K for operation aboard an outer solar system mission, these KIBs should have adequate sensitivity without the need for cryocoolers.

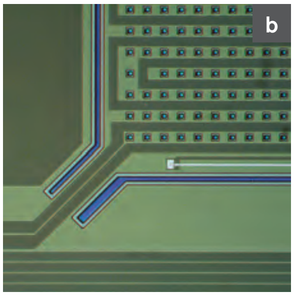
Arrays of the KIBs with microwave readout are in the initial stages of development at JPL, intended to function in the focal plane of an ultra-broadband ultra-sensitive hyperspectral infrared imager, which is also in the initial stages of development. This instrument has the potential to enable detailed measurements of planetary surfaces and atmospheres, including fast hyperspectral imaging of dynamic phenomena such as atmospheric storms to capture their composition, evolution, and three-dimensional structure.

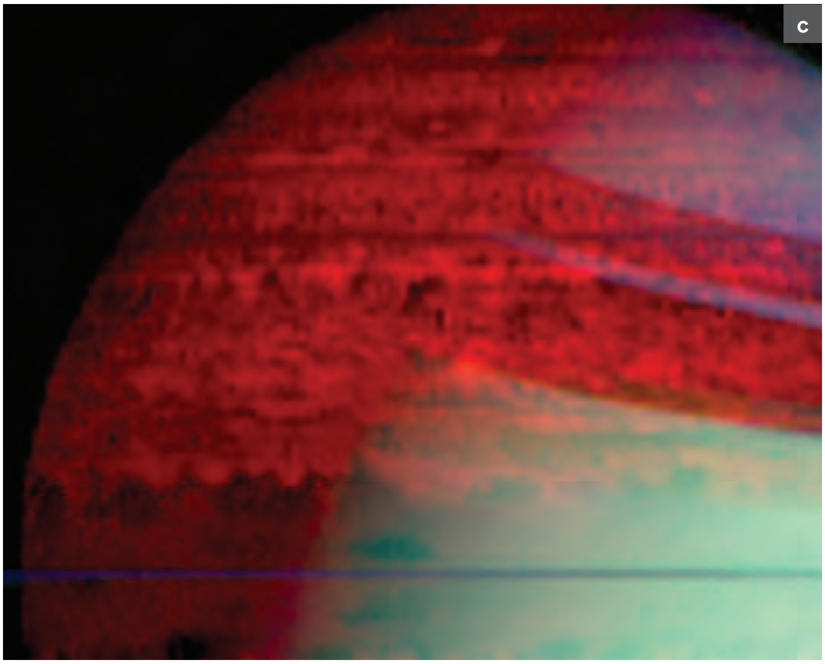
QUANTUM ANNEALING PROCESSOR-RELATED R&D WITH D-WAVE SYSTEMS INC.

FOR THE PAST 11 YEARS, the Superconducting Materials and Devices group has been working in collaboration with D-Wave Systems Inc., a Canadian company that is commercializing quantum computing by building quantum annealing machines based on two-dimensional superconducting qubit arrays. Exploitation of quantum effects provides dramatic speedup and improved solution accuracy. The JPL collaboration with D-Wave emphasizes forward-looking investigations that advance D-Wave technology, with JPL fabricating prototype and test wafers and performing cryogenic measurements aimed at noise reduction, novel circuit designs, device/circuit improvement, and advanced fabrication process development. An outstanding collaborative success in 2015 was the demonstration of a novel frequency multiplexed resonant readout for D-Wave processors.

a Micrograph of a kinetic inductance bolometer based on a superconducting resonator consisting of an interdigitated capacitor (upper left in picture) and an inductive temperature sensor suspended on a thin silicon nitride membrane (upper right). Holes have been etched in the silicon nitride around the inductor, allowing the silicon underneath to be etched away, resulting in a free-standing membrane. A similar device with a smaller capacitor (lower left) and a non-isolated inductor (lower right) is included for comparison. The superconductor linewidths are 10 μm. **b** Micrograph showing an expanded view of a portion of the membrane-isolated inductor. **c** Image of a false-color mosaic of data from the Visual and Infrared Mapping Spectrometer (VIMS) aboard the Cassini mission, illustrating how atmospheric structure can be revealed by a multispectral infrared instrument. Here, short wavelengths (blue-green) image high-altitude clouds and longer wavelengths (red) probe deeper into the atmosphere. The superconducting bolometers are designed to target a wide range of longer wavelengths to probe farther into the atmospheric depths of outer solar system planets and moons, while also enabling detailed characterization of the surfaces of other bodies.







The Submillimeter-Wave Advanced Technology (SWAT) Group of the MDL specializes in developing and implementing submillimeter-wave and terahertz remote sensing technologies for a variety of applications. The group's primary focus is to develop components and technologies to enable spaceborne instruments based on high-resolution heterodyne spectrometers for Earth remote sensing missions, planetary missions, and astrophysics observatories. The group's rich and varied technical expertise is also utilized for ground-based applications that are a spin-off from the heterodyne receiver technologies.

Heterodyne technology allows one to map/detect unique molecular signatures with very high spectral resolution over a wide range of wavelengths. JPL/NASA has been the traditional leader in this field due to its wide applicability for astrophysics as well as Earth remote sensing. We continue to utilize MDL capability to innovate for the next generation of devices, components, and subsystems to enable the next generation of instruments that will be key in exploring other planets or helping to better understand our own planet.

SUBMILLIMETER–WAVE ADVANCED TECHNOLOGY

above. A diverse group of technologists and scientists are involved in developing advanced submillimeter-wave technology for future NASA and national needs. The group's expertise includes MMIC design, CMOS design, heterodyne detectors, cryogenic detectors, novel material and devices, local oscillator technology, THz diodes, submillimeter-wave instrument design, and development and flight hardware delivery.

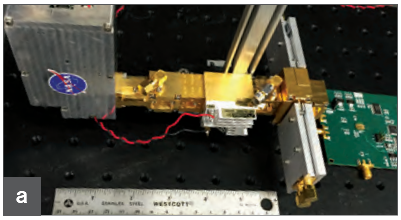
OUR GROWING CAPABILITIES ALLOW US TO PEER INTO THE EARLY UNIVERSE, STUDY COMETS TO DISCOVER WHERE EARTH'S WATER CAME FROM, KEEP US SECURE AT AIRPORTS WITH FAST SCANNING, AND ENSURE EXCITING FUTURE MISSIONS TO VENUS AND THE OTHER PLANETS.

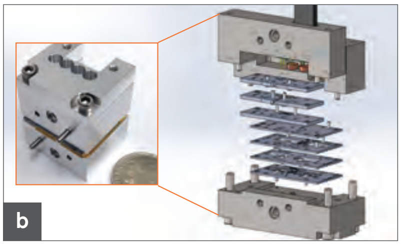
"**DR. JONAS ZMUIDZINAS** has been one of the leading scientists and technologists who pushed hard to make submillimeter-wave technology a core strength at JPL/Caltech. Jonas' insight and leadership in cryogenic heterodyne detectors has been crucial for advancing the state of the art in the field; his seminal work in this field allows us to build more sensitive instruments for the future."

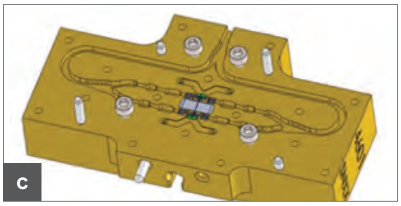
SILICON MICROMACHINED TECHNOLOGY ENABLES COMPACT ATMOSPHERIC INSTRUMENTS

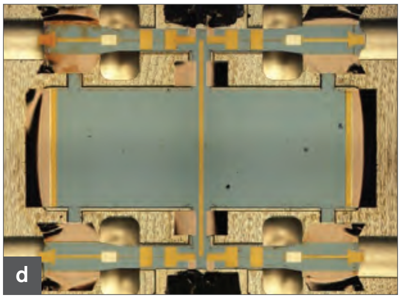
MDL IS DEVELOPING the next generation of THz array transceivers using silicon micromachining. For the past few years, NASA has funded the development of super-compact submillimeter-wave receivers for future JPL instruments. This allows us to build and deploy smaller receivers that are ideally suited for planetary missions. This technology uses a combination of standard photolithographic techniques and dry plasma in order to create very precise 3D patterning of silicon micro-structures. Current state-of-the-art THz receivers are being fabricated using metallic blocks (size is around 1cm^3 each), where each metal block corresponds to a transceiver component (mixer, amplifier, combiners, multipliers, etc.). The aim of this technology is to compact all these elements into a 0.5cm^3 silicon chip, with vertical 3-dimensional (3D) integration of all the components. By compacting all these elements, we are not just reducing the mass and volume of the instrument, we are also improving the sensitivity and overall performance of these systems.

The Planetary Instrument for Submillimeter-wave Surface and Atmospheric Reconnaissance and Research in Orbit (**PISSARRO**) is an instrument partially being developed at MDL that will replace the current generation of bulky, high-power-consumption radiometer/spectrometers. It will operate in the 520-600 GHz band, and will provide a state-of-the-art submillimeter-wave radiometer with a brassboard spectrometer, for orbiter missions to Mars, Venus, and Titan, or to the Galilean moons. This instrument, whose heart is built entirely using silicon micromachining, is improving the sensitivity by more than a factor of two, and the overall power consumption by a factor of four. This is the only instrument developed at JPL that is capable of resolving wind speed, temperature, pressure, and composition in the critical upper layer of the atmosphere. The radiometer will allow the detection of a large number of chemical species such as H_2O, N_2O, NO_2, NH_3, SO_2, H_2S, among others, at concentrations below a part by billions. The spectrometer will characterize the atmosphere with high spectral, spatial, and temporal resolution uniquely available through submillimeter-wave observations. These results can uniquely provide understanding of the geological processes that are formed in the planetary body and its surface.







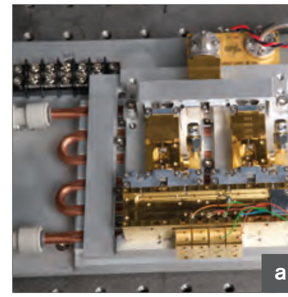


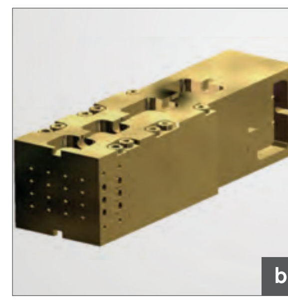
a. 550-GHz, dual-polarized sideband-separated receiver with silicon micromachined waveguide packaging. Silicon micromachined waveguide components are vertically stacked to form the highly integrated receiver front-end. **b.** MDL has built up advanced silicon micromachining capability that allows researchers to design and build submillimeter-wave components and instruments that are compact and well-suited for planetary missions. **c d.** By utilizing advanced lithographic techniques available at MDL, JPL researchers have developed compact on-chip power combiners that allow manufacturing of high-power sources in the submillimeter-wave range, enabling atmospheric instruments with increased coverage.

GaAs SCHOTTKY DIODE MULTIPLIER CHIP SETS NEW WORLD RECORD FOR OUTPUT POWER AT 200 GHz

ELECTRONICALLY TUNABLE SOLID-STATE SOURCES are a key building block for a future generation of submillimeter-wave instruments. GaAs Schottky diode technology has a long history of being able to provide sources; however, current chip designs are severely limited by how much input power can be coupled to them due to heating and number of anodes. A novel solution proposed by MDL engineers and fabricated at the MDL involves on-chip power combining. In this approach, a number of chips are combined in a novel topography to drastically increase the power-handling capability of the chip. A chip with 24 anodes has been designed and demonstrated. This is a 180-GHz doubler that will be used to drive additional frequency multipliers to reach 4.7 THz. The chip has demonstrated state-of-the-art conversion efficiency and produces > 500 mW of output power at 180 GHz, which is a new world record.

MDL-developed technology for multi-pixel heterodyne receivers has been proposed in an instrument for the SOFIA Observatory. This technology will enable mapping speeds that are considerably faster than current instruments.





MULTI-PIXEL INSTRUMENTS ON BOARD BALLOONS AND AIRCRAFT WILL MAP OUR GALAXY

STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY (SOFIA) is a NASA-funded modified 747 aircraft observatory. We are currently proposing to build a multi-pixel imaging spectrometer that will help to address a key problem in modern astrophysics: understanding the life cycle of star-forming molecular clouds in our Milky Way Galaxy. To accomplish this goal, SOFIA will survey a section of the Galactic Plane in the luminous interstellar cooling line at 158 microns (1.90 THz) and the important star-formation and ionized gas tracer at 205 microns (1.45 THz). The multi-pixel heterodyne receiver arrays on board SOFIA possess the sensitivity and spectral resolution needed to see molecular clouds in the process of formation, measure the rate of evaporation of molecular clouds, and separate the bulk motion of gas in our Galaxy from local kinematic effects. By building a three-dimensional picture of the interstellar medium of the Galaxy, SOFIA will be able to study the creation and disruption of star-forming clouds in the Galaxy, determine the parameters that govern the star formation rate, and provide a template for star formation and stellar/interstellar feedback in other galaxies. JPL's MDL is at the forefront of producing the local oscillator and hot electron mixers for this important mission.

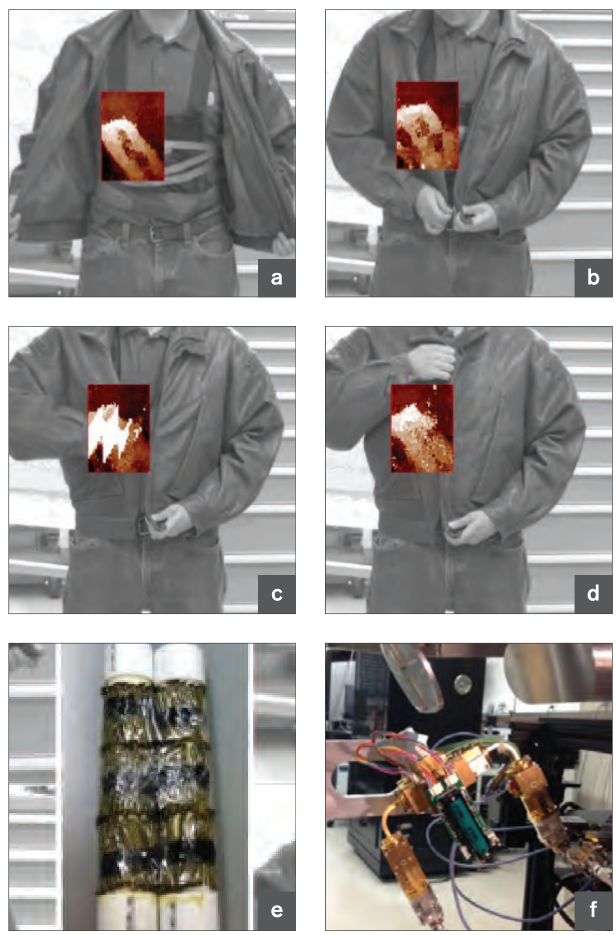
a-c: MDL researchers have utilized advanced THz MMIC technology to design, build, and demonstrate world-record output power from Schottky diode multipliers in 200-500 GHz range. d: MDL researchers were part of the team that built the Stratospheric THz Observatory, a long-duration balloon observatory to be launched from the South Pole. Here the team members are shown after a successful hang test at a NASA facility. e: JPL engineers are working in the hangar at the South Pole to integrate and test the heterodyne receiver arrays for the Stratospheric THz Observatory, a balloon submillimeter-wave observatory.

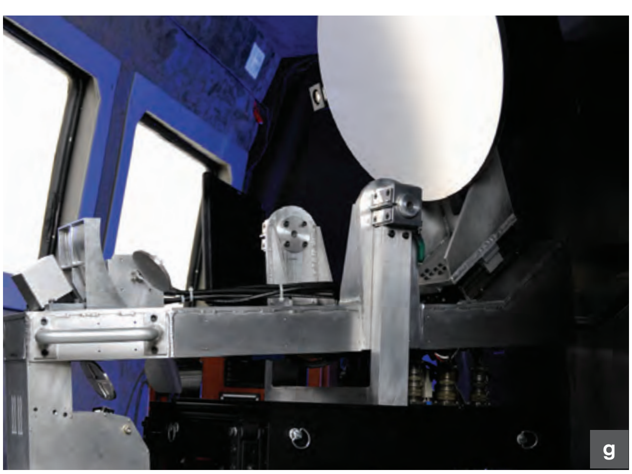
MDL scientists study dust storms in the Mojave Desert.

MDL LEVERAGES SPACE TECHNOLOGY FOR A SAFER PLANET EARTH

SUBMILLIMETER-WAVE components and receivers that have been developed for space applications can also be used for applications on planet Earth. A portable radar system was demonstrated in 2014 that can provide imaging of targets by revealing artifacts behind clothes (which are undetectable with regular cameras). In 2015, this radar system was upgraded by utilizing a multi-pixel RF module. This allowed us to make images with a much faster readout time (real time-imaging), enabling us to monitor larger scenes. The technology developed at JPL, based on devices from MDL, can work at 340 GHz and 670 GHz, the highest reported frequency for such an application. This breakthrough allows one to image a wide scene with centimeter-scale resolution. This instrument has scientific applications for studying the dynamics of dust storms or volcanic eruptions on Earth as well as on other planets. This system is portable and can be mounted in a vehicle, as was done by MDL scientists to study dust storms in the Mojave Desert.

MDL RESEARCHERS HAVE UTILIZED ADVANCED THz MMIC TECHNOLOGY TO DESIGN, BUILD, AND DEMONSTRATE WORLD-RECORD OUTPUT POWER FROM SCHOTTKY DIODE MULTIPLIERS IN THE 200-500 GHz RANGE.



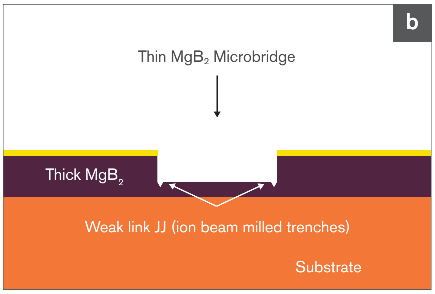


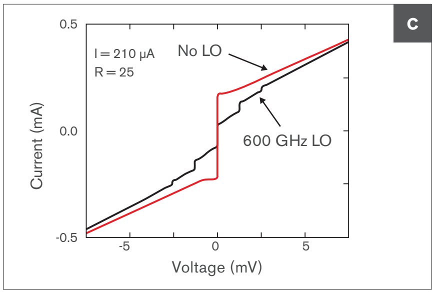
a-e The 340-GHz transceiver array has now enabled 8.3-Hz frame rate through-clothes standoff radar imaging for personnel screening security applications. Here are four frames of a movie including the real-time overlay of 340-GHz radar imagery of a fake pipe bomb (e) hidden underneath a heavy leather jacket. **f** Front-end of a 340-GHz imaging radar, showing a linear array of four submillimeter-wave transceivers based on MDL-fabricated Schottky diodes and a compact stack of MDL-fabricated micromachined silicon waveguide. **g** Portable imaging radar system.

NOVEL HIGH-T_C MATERIAL HELPS TO ADVANCE THz RECEIVERS, GENERATES NEW DEVICE IDEAS

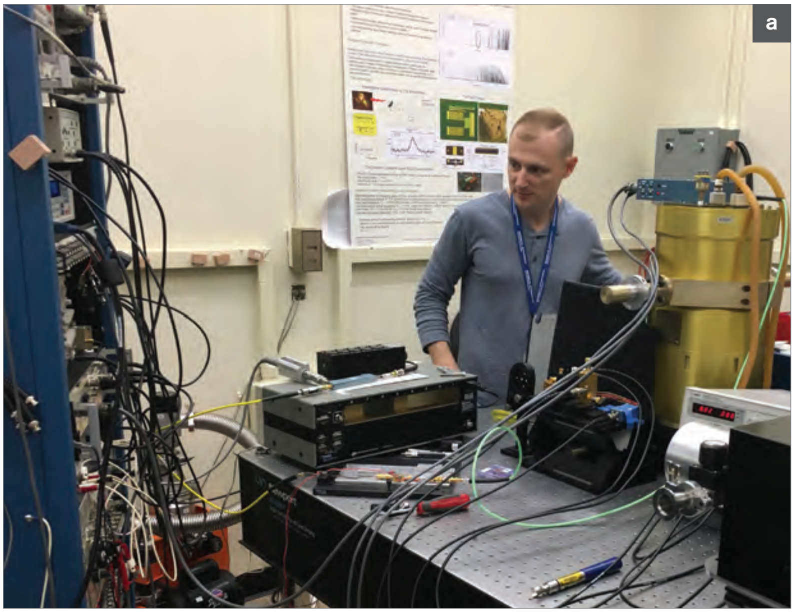
MDL IS PURSUING THE DEVELOPMENT OF A NOVEL HOT-ELECTRON BOLOMETER (HEB) mixer for applications at very high THz frequencies (e.g., detection of the (OI) line at 4.7 THz). The work employs unique thin superconducting films made from high-TC MgB_2 superconductor. The benefits of this work will be a possibility to operate an instrument on space telescopes using mechanical cryocooling and an increase of the intermediate frequency bandwidth by a factor of three compared to current HEB mixers. Achieving the technical objectives of this work will significantly advance the state-of-the-art of heterodyne instrumentation for high-resolution THz spectroscopy. THz antenna-coupled devices of micron and submicron size are fabricated at MDL.

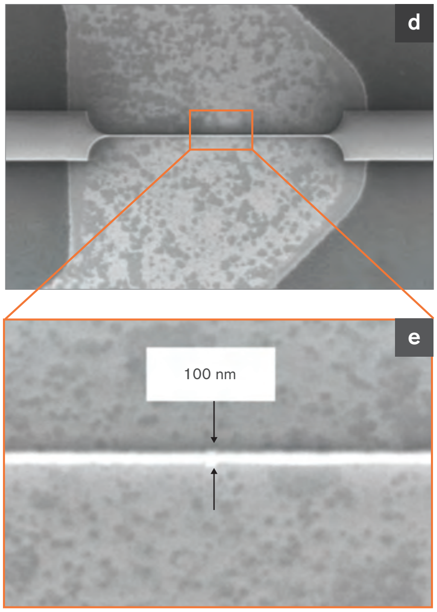
As a spin-off of the HEB mixer development effort, the new MgB_2 tunnel-junction technology extending the frequency range of Superconductor-Insulator-Superconductor (SIS) or Josephson Junction (JJ) mixers up to 2 THz is being addressed. The first mixing results at 600 GHz are very promising. Besides the mixers, future applications may include on-chip local oscillators for multipixel receivers based on flux-flow JJ devices and SIS based frequency multipliers.





a Dr. Daniel Cunnane is carrying out THz characterization of an HEB mixer. The THz mixer test lab has a unique selection of LO sources including an optically pumped molecular gas laser, a quantum cascade laser, and Schottky-diode based frequency multipliers. The current mixer devices operate in a receiver cooled with liquid helium. However, as the technology matures, the test system will be upgraded with a mechanical cryocooler operating at ≈ 20 K. High-temperature operation is one of the strongest advantages of the MgB_2 based sensors for potential applications in space instruments where cryocooling is difficult and expensive. **b** A new type of tunneling superconducting (Josephson) junction was achieved in MgB_2 films. The devices were produced by ion milling narrow trenches in the narrow bridge in which the superconductivity is weakened. **c** The junction demonstrated very distinctive "Josephson" behavior under pumping by 0.6-1.9 THz radiation. The width of so-called Shapiro voltage steps in the current voltage characteristic is proportional to the radiation frequency. The very high frequency at which this Josephson mixer operates is due to the large superconducting gap present in MgB_2 for tunneling in the in-plane direction. Conventional (low-T_C) Josephson mixers have a smaller gap and cannot reach such high frequencies. **de** Submicron-wide superconducting bridges have been fabricated from MgB_2. This is an important step in achieving very small HEB mixer devices. The HEB device size determines the amount of the required LO power. This quantity must be minimized for operation at high THz frequencies where LO sources are relatively weak. Another motivation for device miniaturization is the set of constraints imposed by the integrated planar antenna, which can typically accommodate devices not greater than just a few microns.





“**JONAS ZMUIDZINAS’** deep commitment to MDL and his strategic thinking have had a profound effect on how we identify and develop relevant technologies.”

NANO & MICRO SYSTEMS

The Nano and Micro Systems Group and close collaborators. Front row[L to R]: Harish Manohara, Karl Yee, Linda Del Castillo, Lauren Montemayor, Mohammad Mojarradi, and Bala Balakrishnan. Back row[L to R]: Eshwari Murty, Ronald Korniski, Victor White, Risaku Toda, and Valerie Scott.

INNOVATIVE INSTRUMENTS

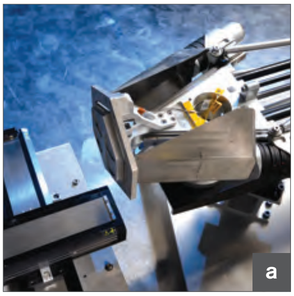
APPLICATION-DRIVEN NANO AND MICRO DEVICES AND TECHNIQUES, DEVELOPED THROUGH THE NANO AND MICRO SYSTEMS EFFORT AT MDL, ARE VITAL TO IN SITU AND REMOTE PLANETARY EXPLORATION.

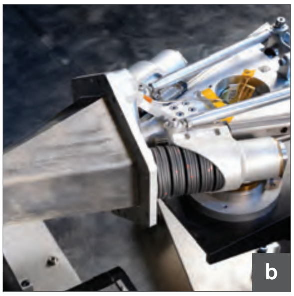
The Nano and Micro Systems Group was formed to bring together micro- and nanotechnologies under one roof so that the technology research can move beyond component-level development into the level of miniature systems. This was the vision, and it has led to a sustained R&D effort in niche areas including carbon nanotube field emission devices, electron-beam-based miniature systems, micro gyroscopes, black silicon-based imaging spectrometer components, and the world's smallest 3D imaging camera (3D-MARVEL), among other things.

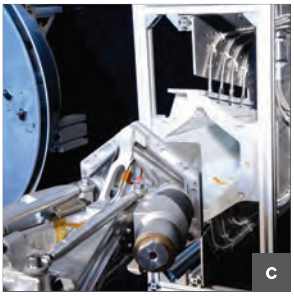
The reason for success in these projects can be attributed to the collaboration and exemplary work ethic among group members, and extraordinary support from the MDL leadership team. In particular, we thank Dr. Jonas Zmuidzinas, the JPL Chief Technologist, who served as the first MDL Director. Jonas has influenced all of the group's work either directly or indirectly, and has been responsible for enhancing MDL's stature among the research community.

The NAMS group has been the beneficiary of his commitment to support any work he believes in. Recently, Jonas lent the weight of his office as a show of support to win the critical phase of a large technology development project involving commercial sponsors. During the proposal review, he strongly endorsed the proposal and our approach to the industrial visitors: he narrated the story of how Dr. Erik Fossum and his team first developed the active pixel sensor (APS) at JPL.

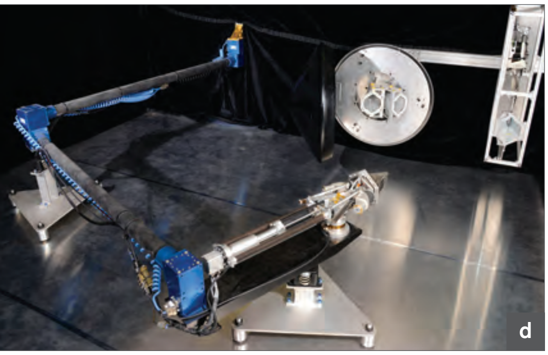
This was impressive in that one of the critical components of the proposed development is a custom image sensor. Jonas' narrative unequivocally underscored the credibility of the project team, and of MDL as one of the most well equipped laboratories to conduct this research. This project is now moving forward and we think Jonas' advocacy in that meeting was a major factor.

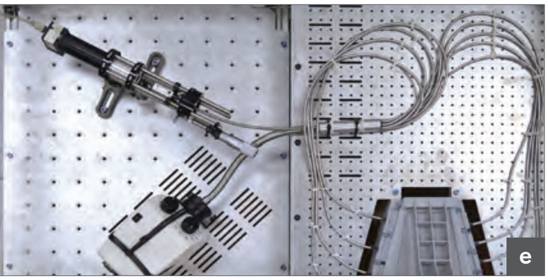


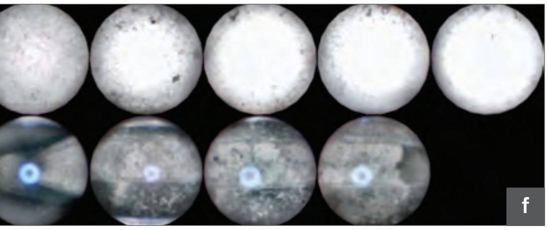




BiBlade comet surface sampler testbed.







FIBERSCOPE SAMPLE IMAGING SYSTEM FOR ROBOTIC COMET SURFACE SAMPLE RETURN MISSIONS

A FIBERSCOPE-BASED SAMPLE VERIFICATION SYSTEM is currently being developed for a potential robotic comet surface sample return mission. In this mission concept, the spacecraft would perform a touch-and-go maneuver at a small body to collect comet surface samples. Immediately after the sample is captured, the fiberscope sample verification system would perform in situ verification of the comet sample. If the captured sample quantity was deemed insufficient, the sample collection maneuver would be re-attempted, multiple times if necessary, until a baseline sample volume is positively confirmed.

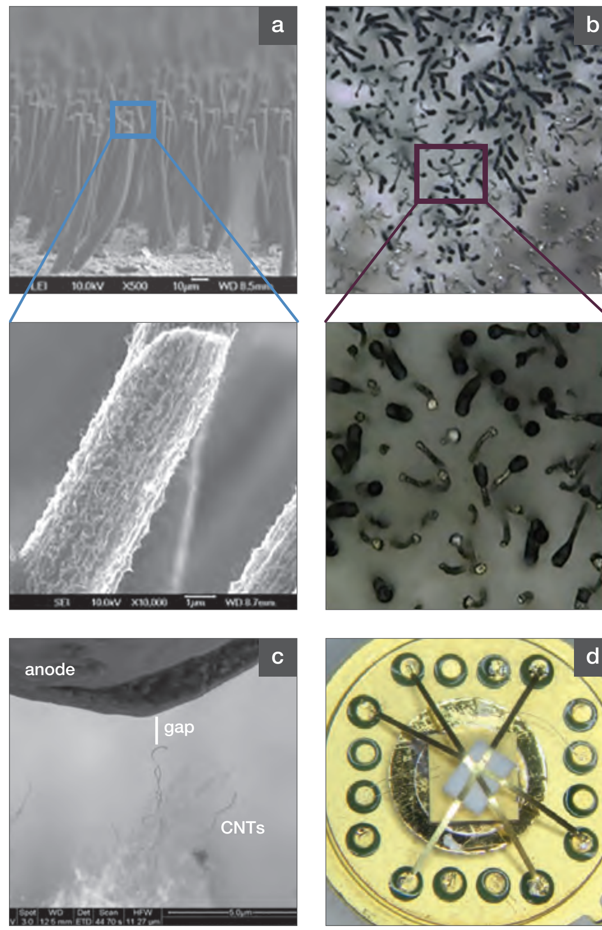
The proof-of-concept fiberscope sample imaging system hardware shown here consists of nine imaging fiberscopes integrated into a single bundle. The obtained nine images are analyzed to map spatial distribution of the collected comet sample in order to estimate the sample quantity. The achieved image resolution is in excess of 4 line-pair/mm at 20 mm working distance. Surface color and texture of a comet sample simulant would clearly be discernible at this fidelity. The distal end of these fiberscopes is designed to tolerate the harsh temperature and radiation environment near a comet, while sensitive electronics and optical components at the proximal end can be placed in the more benign electronics bay of the spacecraft.

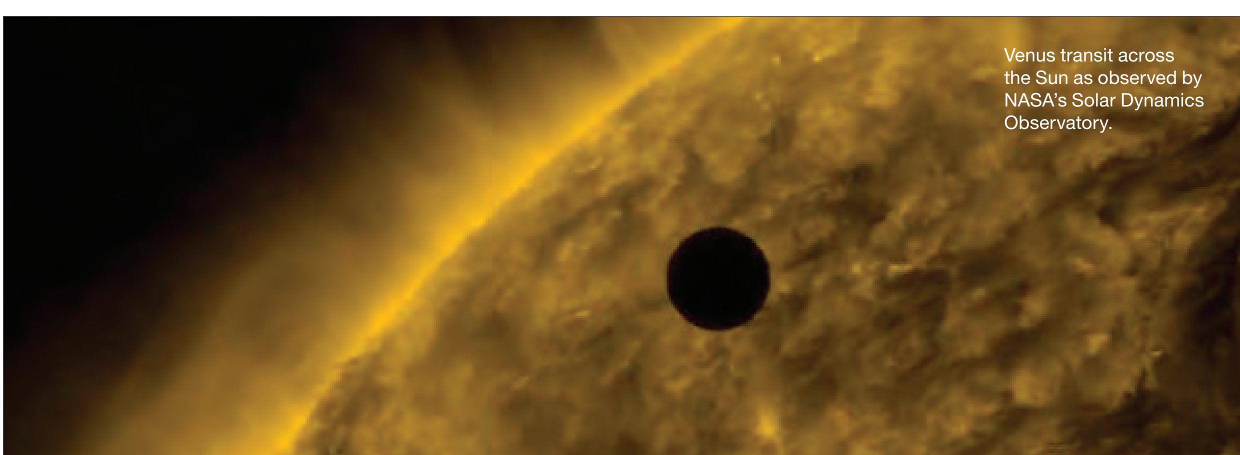
a. BiBlade pulls open before comet touch-and-go sampling operation. **b.** BiBlade inserted into sample measurement station. The BiBlade opens slightly (~5 mm) so the nine fiberscopes can capture the sample image for verification. **c.** BiBlade closes and encapsulates comet sample within 40 milliseconds. **d.** Robot arm transfers the sample to sample return capsule. **e.** Nine bundled fiberscopes looking inside of sample measurement station. **f.** Fiberscope image of comet sample simulant.

HYBRID CNT TRIODES FOR HIGH-TEMPERATURE ANALOG CIRCUITS

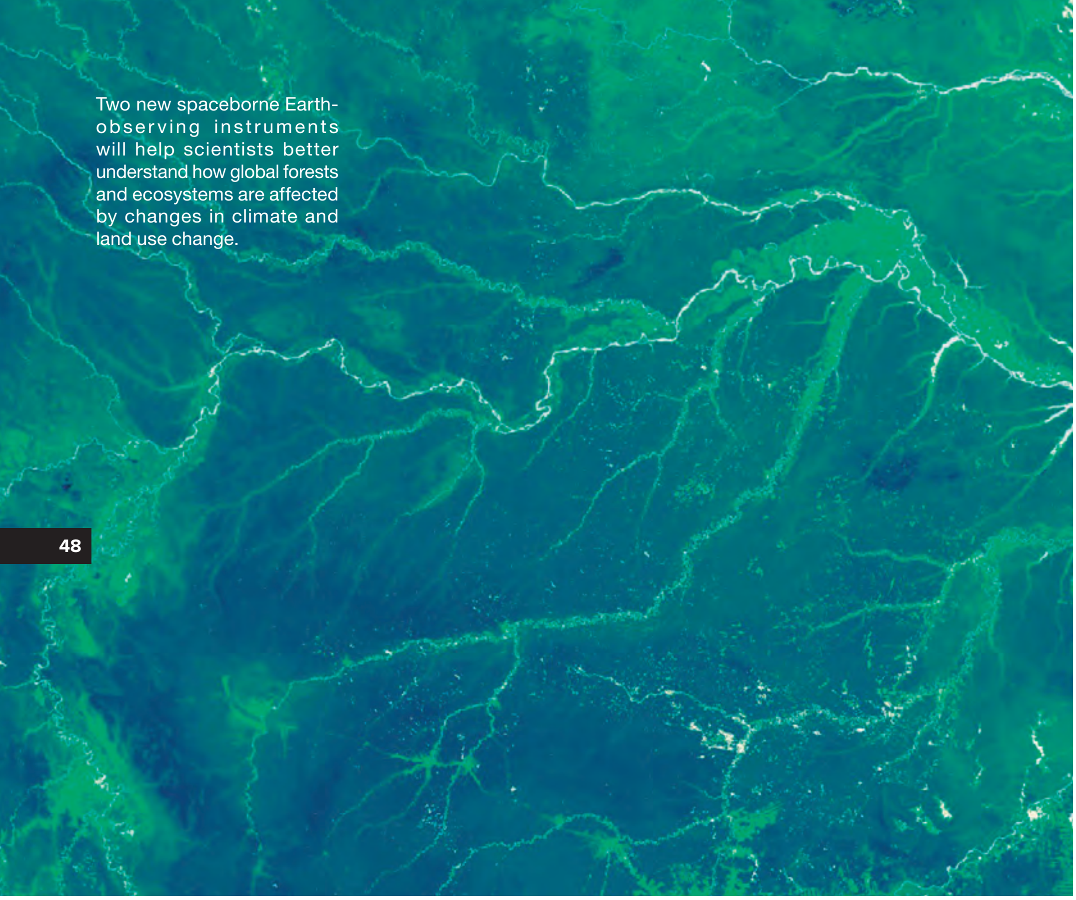
WITH FIELD DEMONSTRATION IN VIEW, last year's focus has been on increasing the robustness of CNT-based vacuum electronic devices. The goal for these devices is to function optimally in high-temperature environments, for both commercial and planetary instruments for prolonged and uninterrupted operation. These devices are fabricated using a hybrid assembly process, which entails building the device up in layers. An electrode stack consisting of a carbon nanotube (CNT) cathode, commercial off-the-shelf (COTS) gate, and anode is mounted onto a COTS header. Carbon nanotubes have been successfully attached to this header (both electrically and mechanically) in two ways using proprietary processes developed at JPL. The device assembly, consisting of the electrode stack and the header, is attached to a vacuum tube header where it is then sealed under high vacuum inside a small glass tube. These devices have been successfully tested up to temperatures of 250° C while maintaining functional requirements. In preparation for immediate field testing for commercial applications, efforts of the past year have been focused on overcoming the challenges regarding the robustness of the device, reliability, functionality, and optimization of CNT attachment methods.

a Scanning electron micrographs of a conductive epoxy wicked carbon nanotube (CNT) cathode and **b** Optical micrographs of a brazed CNT cathode. **c** Image of field emission tests done inside a scanning electron microscope. An electrode stack attached to TO8 header before (**d**) and after (**e**) vacuum packaging.

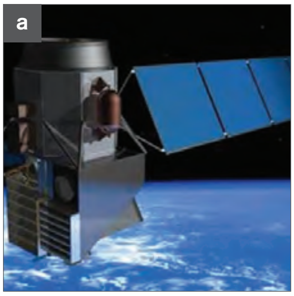


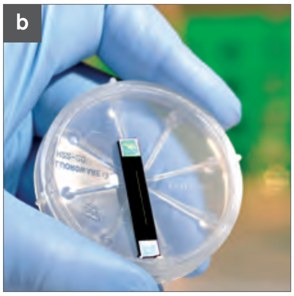


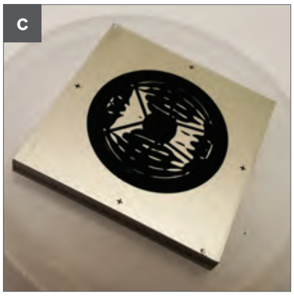
Venus transit across the Sun as observed by NASA's Solar Dynamics Observatory.



Two new spaceborne Earth-observing instruments will help scientists better understand how global forests and ecosystems are affected by changes in climate and land use change.



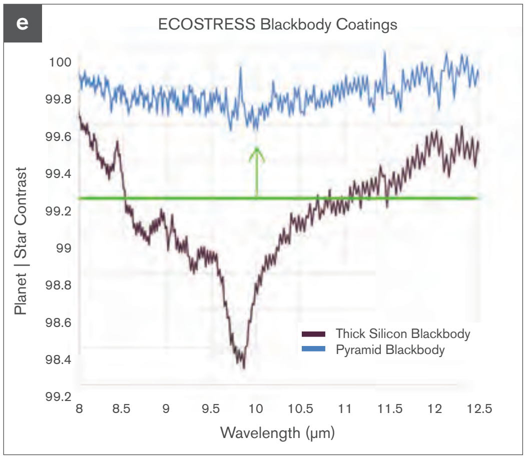




JPL BLACK SILICON TECHNOLOGY

PER THE 2010 NASA DECADAL SURVEY, technology advancement of high-contrast imaging in space was identified as the item of highest priority at medium scales. Recent progress at JPL on the WFIRST-AFTA program has enabled more than 4 orders of magnitude contrast enhancement beyond state-of-the-art high-contrast imaging masks. This was achieved by micromachining ultra-black surfaces using JPL's black silicon process. These masks will enable imaging of new classes of exoplanets through removal of the light from the parent star.

Slits with black silicon as an anti-reflection surface have been incorporated into JPL flight spectrometers HyTES, UCIS, HyspIRI, MaRS2, PRISM, NEON, and SWIS, and are baselined for all future JPL spectrometers as well. The low reflectivity of black silicon also gives it a very high emissivity. For this reason, the ECOSTRESS and CIRAS missions will be utilizing black-body calibration targets made of black silicon.

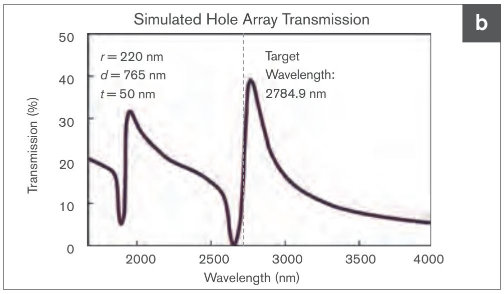


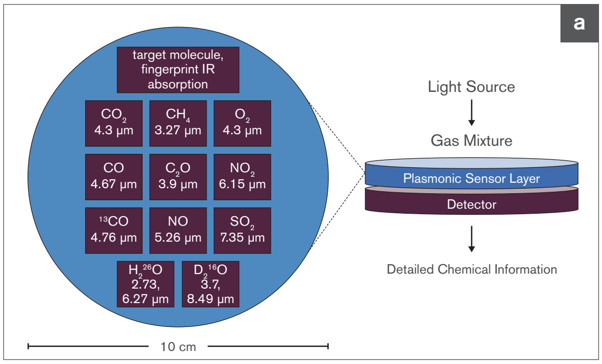
a. The data from HyspIRI would be used for a wide variety of studies primarily in the carbon cycle and ecosystem and Earth surface and Interior focus areas. b. Development of black Si technology to enhance the performance of imaging spectrometers for Earth science applications. c. High-contrast imaging mask shown in inset. (From the WFIRST-AFTA 2015 Report). d. SWIS spectrometer slit and ECOSTRESS blackbody tile. e. Emissivity data of black silicon compared with program requirement for ECOSTRESS (green line) and with a pyramidal blackbody (red line). f. Sensitivity of WFIRST-AFTA optics with comparisons to Hubble Space Telescope (HST) and James Webb Space Telescope (JWST). (page 49).

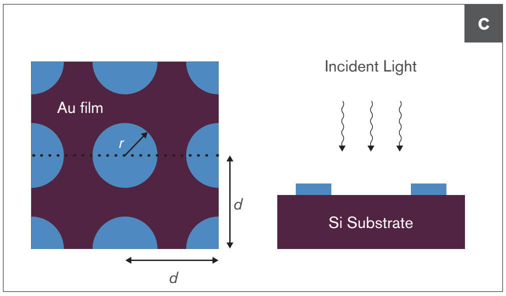
ASSESSING PLASMONIC INFRARED NANOSENSORS FOR SELECTIVE TRACE GAS DETECTION

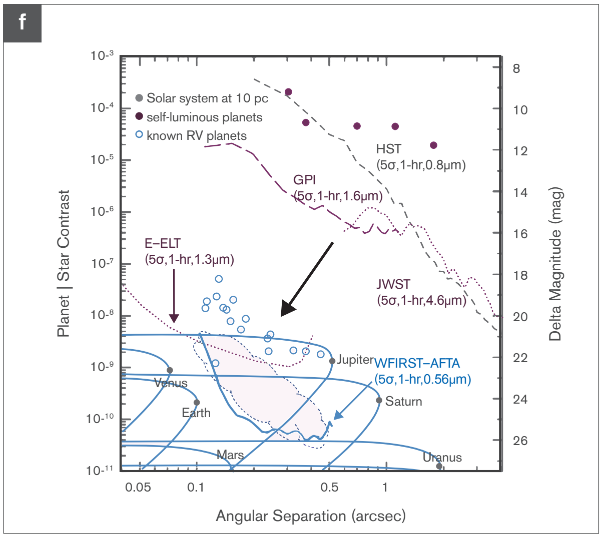
MANY NASA MISSIONS demand small, selective, and sensitive gas sensor technology. Infrared spectroscopy offers extraordinary selectivity through highly specific fingerprint absorptions. While most existing plasmonic sensors function by measuring the plasmon resonance frequency shift due to the changing refractive index of the surrounding medium, this technology has potential to be used as extremely selective and sensitive IR absorption sensors, where the sensors can be matched to target molecule resonances and enhance the resulting signals relative to measurements based on free-space transmission. The goal of this project was to first design and fabricate IR filters based on plasmonic nanohole arrays and then to measure the relative absorption enhancement without active surface concentration. To maximize absorption due to gas interaction near the array surface, measurements were conducted in a cell with a minimal free-space path length. Calculations indicated enhancements of 10^2-10^3 should be detected under the conditions tested. Experimental enhancements were too small to be picked up over the free-space absorption signal. These arrays may have promise as optical filters with minimal enhancement to be used in a device similar to what was originally envisioned, and, compared with traditional IR filter technology, they are based on a more scalable single-layer fabrication process.

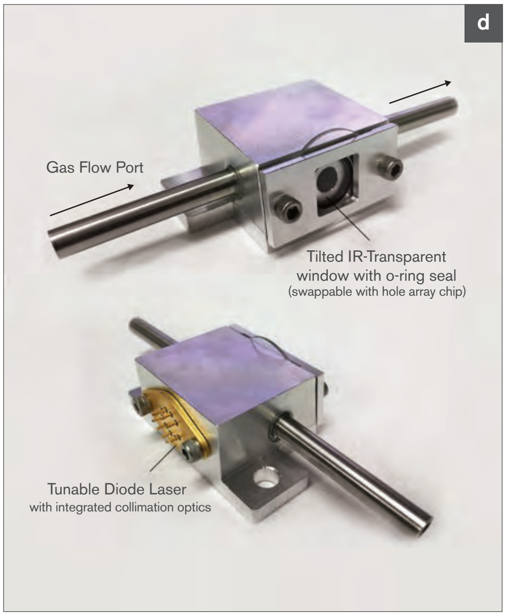
a. Device concept and full-field electromagnetic simulations results of the CO_2 absorption matched extraordinary-transmission plasmonic hole array. **b.** Simulated hole array transmission. **c.** Nanohole design. **d.** A custom flow cell designed for measuring laser transmission near 2784.9 nm with varying CO_2 concentration.

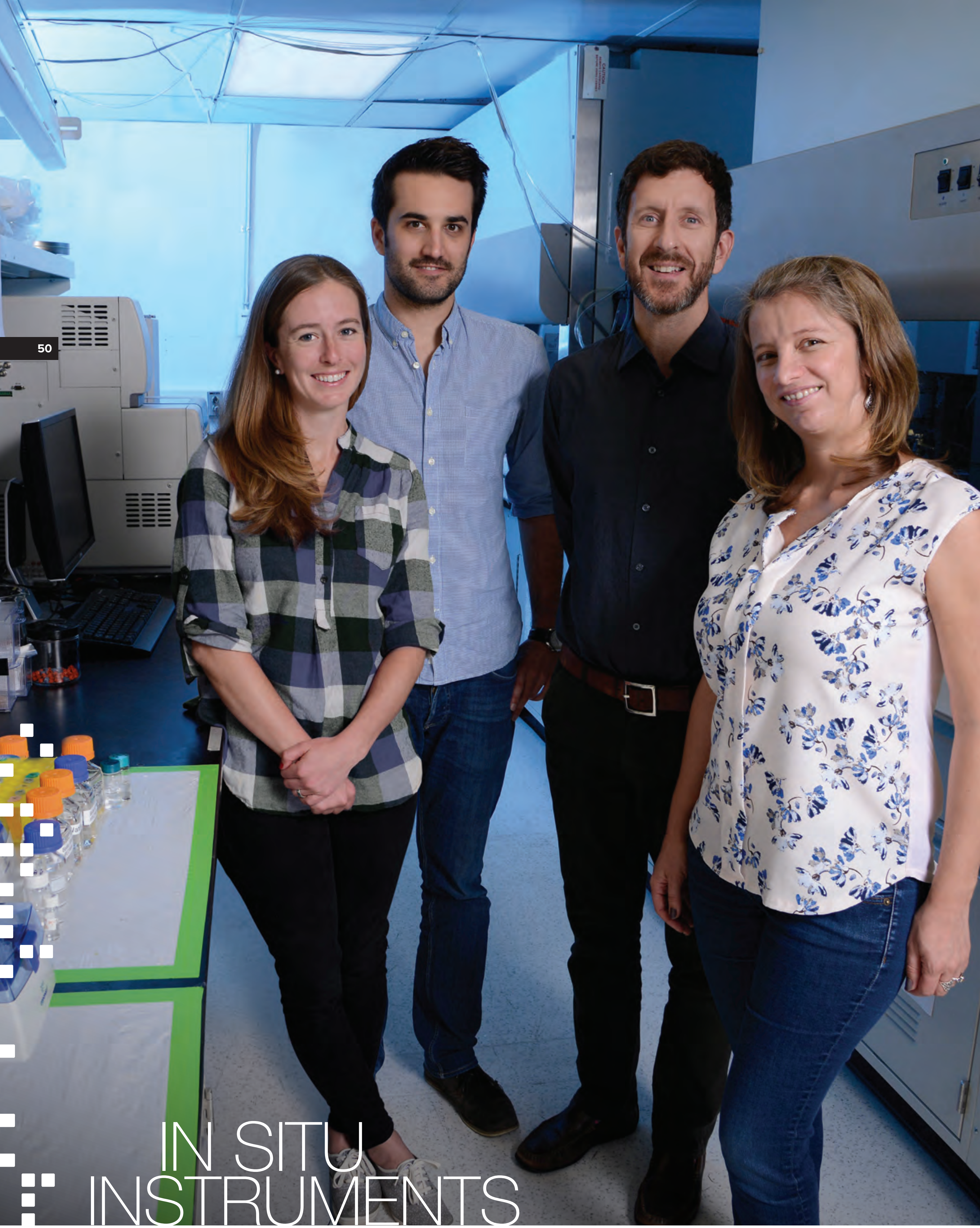












IN SITU INSTRUMENTS

Willis Lab [L to R]: Jessica Creamer, Florian Kehl, Peter Willis, and Fernanda Mora.

TECHNOLOGIES OF THE FUTURE

THE CHEMICAL LAPTOP IS THE FIRST BATTERY-POWERED, AUTOMATED, REPROGRAMMABLE, PORTABLE ASTROBIOLOGY INSTRUMENT.

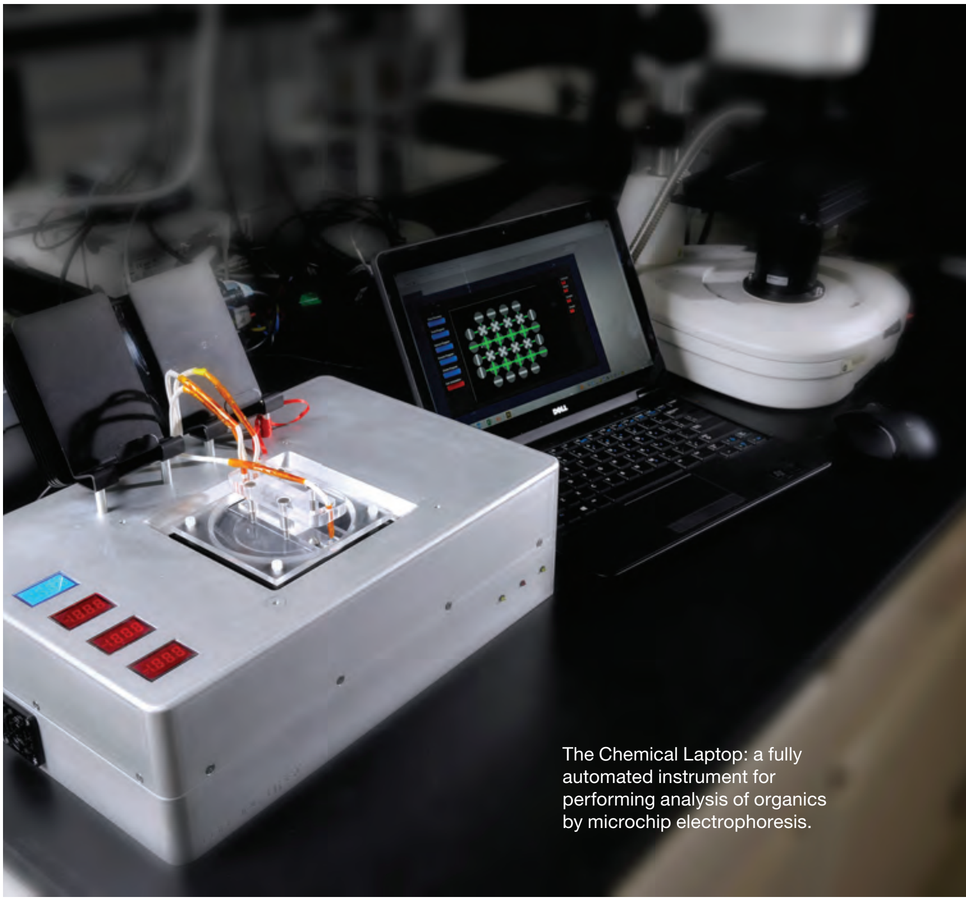
Peter Willis has been at JPL for 12 years working toward the development of in situ instrumentation to search for the biochemical signs of life on other planets. At the most basic level, all life on Earth is fundamentally the same, constructed from a relatively small set of chemical building blocks. By analyzing the distributions of organic molecules on other worlds, we can search for the pattern of these building blocks that can provide clues about the presence of extinct or extant life. In this search for life in the universe, an instrument capable of liquid-based chemical analysis is needed. This requirement for liquid analysis is not surprising: it was in water that life evolved on Earth and through liquid-based techniques that we have greatly augmented our understanding of biology and complex biological processes.

Microchip electrophoresis with laser-induced fluorescence (ME-LIF) detection is a liquid-based technique, and it provides efficient separations for a variety of these building blocks such as amino acids or fatty acids. Specific molecular properties of these organic acids (chirality of amino acids and carbon chain length of fatty acids) are useful biomarkers, should they be detected in extraterrestrial environments.

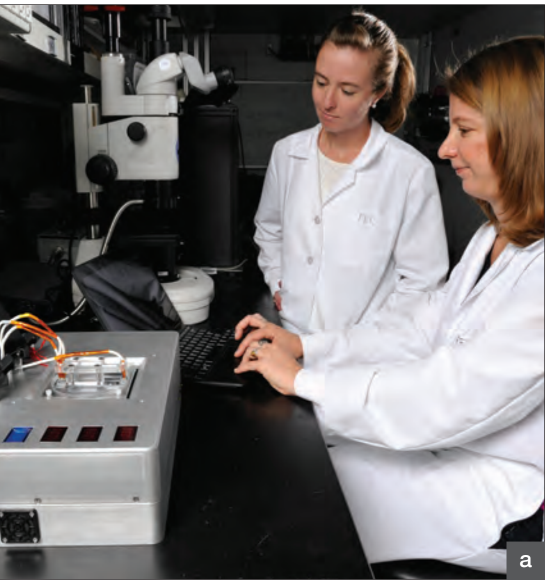
When Peter first joined JPL, he was part of Frank Grunthaner's group which, in collaboration with UC Berkeley, was developing the in situ instrument using ME-LIF for the specific task of analyzing soil samples for the presence of amino acids. The extraction and separation components of this instrument, named after Harold Urey, was field tested in the Atacama Desert, detecting low parts per billion levels of chiral amino acids. Following selection and subsequent descoping of the Urey Instrument from the ESA ExoMars Mission, Peter started his own lab at JPL and continued to work on this concept.

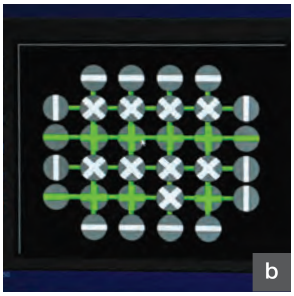
Early on, the Willis Lab benefited from the hard work of several employees and postdoctoral fellows. Working with Peter on his vision, postdocs Fernanda Mora, Morgan Cable, and Amanda Stockton contributed advancements in hardware and methodology. In collaboration with Los Gatos Research, the Willis group designed and built the Chemical Laptop. The Chemical Laptop is the first battery-powered, automated, reprogrammable, portable astrobiology instrument. The Chemical Laptop houses the microfluidic, electronics, and optics needed to perform highly sensitive ME-LIF analysis of organic acids and other organic biomarkers.

Moving into the future, Fernanda Mora was hired as an employee and continues to tackle the challenges of developing a fully automated end-to-end analysis. Postdoctoral fellow Jessica Creamer was brought on to improve the state-of-the-art analysis of chiral amino acids with ME-LIF, increasing the sensitivity to parts per trillion or lower. And to build new hardware, postdoctoral fellow Florian Kehl was hired earlier this year. He will be working towards coupling the ME-LIF separation system with an extraction and to increase the TRL of the entire endeavor.



The Chemical Laptop: a fully automated instrument for performing analysis of organics by microchip electrophoresis.





FATTY ACID ANALYSIS

THE SEARCH FOR EVIDENCE of past or present life on alien worlds starts with the detection of organic signatures essential for life on Earth. Towards this end, JPL has developed a new strategy for analyzing fatty acids on our microfluidic devices.

Fatty acids are found in the cell membranes of all three kingdoms of life on Earth and normally account for 5-10% of microbial biomass. Thus, by analyzing these molecules it would be possible to identify the remains of microorganisms present in extraterrestrial samples.

Terrestrial microorganisms have cell membranes with different carbon chain length signatures. For example, algal fatty acids tend to be around the C20/C22 mark whereas bacterial fatty acids are typically C16-C18 in length. Our microfluidic analyzer distinguishes a broad range of fatty acids by the length of their carbon chains. Thus, by measuring these molecules in an unknown sample, we can find information about what organisms were present, even if the sample is very old and the organisms are no longer alive.

In 2014, MDL demonstrated the analysis of the full range of short to long fatty acids (C2-C30) for the first item on a microfluidic device. A new fluorescent dye was used to label the carboxylic acid in a two-step, one-pot reaction to enable detection via laser-induced fluorescence. Fatty acids were successfully detected in a sediment sample from the Snake Pit hydrothermal system of the Mid-Atlantic Ridge, demonstrating the potential of this method to help characterize microbial communities through target biomarker analysis.

a. Jessica Creamer and Fernanda Mora sending commands to the Chemical Laptop from a computer. b. The computer program interface for pumping liquids on the Chemical Laptop. c. A closeup of the liquid handling stage on the Chemical Laptop.

LAB-ON-A-CHIP INNOVATIONS CAPABLE OF ANALYZING COMPLEX ORGANICS WILL INTEGRATE OUR NATURAL AND TECHNOLOGICAL WORLD THROUGH LIQUID-BASED TECHNOLOGIES OF THE FUTURE.

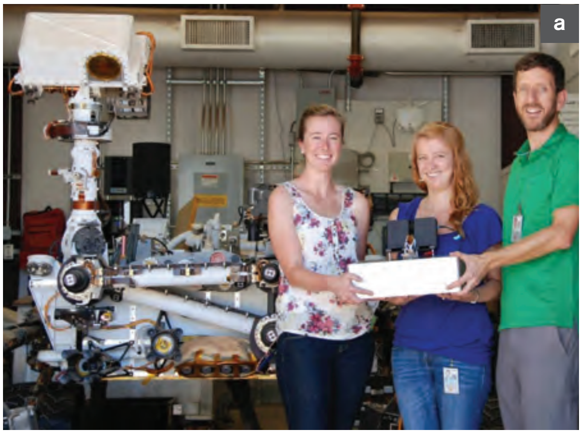
AMINO ACID ANALYSIS

IN ADDITION TO FATTY ACIDS, amino acids have incredible potential as biomarkers for extant and extinct forms of life. Amino acids are the building blocks of proteins, and all life on Earth. A key feature of amino acids is that they exist in one of two equivalent, mirror-image forms, like your hands (b). This geometric property, known as chirality, is the most unambiguous measure of extant life that we possess in the biochemical search for life on other worlds. While meteorites and other non-biological organic samples of material contain 50/50 mixtures of the left- and right-handed versions of these molecules, living material contains only left-handed amino acids.

While past efforts in the development of microchip systems and methods for high-sensitivity chiral resolution of different amino acid types have been limited to just a handful—3 to 5 amino acids in an extraterrestrial analog sample—we have developed methods for the simultaneous resolution of up to 7 at one time. Figure C shows an example of two separations in which 5 amino acids are chirally resolved in just under 40 minutes, using conditions developed at JPL by award-winning NASA Postdoctoral Program scholar Jessica Creamer. Additionally, we have developed a new computational method for rapid visualization of the chiral resolution of very complex mixtures of amino acids, based upon separation efficiency of individual amino acid pairs (d).

a The Willis Lab with the Chemical Laptop in the Mars Yard next to the working replica of the Curiosity rover. **b** Chirality is a chemical characteristic of molecules that are non-superimposable mirror images, like your hands. **c** Two separation conditions capable of resolving 5 pairs of chiral amino acids; this is an improvement on the previous state-of-the-art method for microchip electrophoresis. **d** Plots generated by a computer program written in the Willis Lab to help visualize resolution in complex separations.

a



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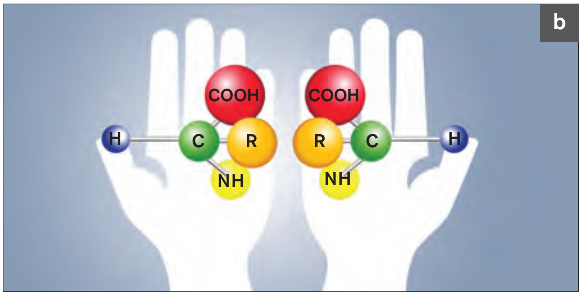

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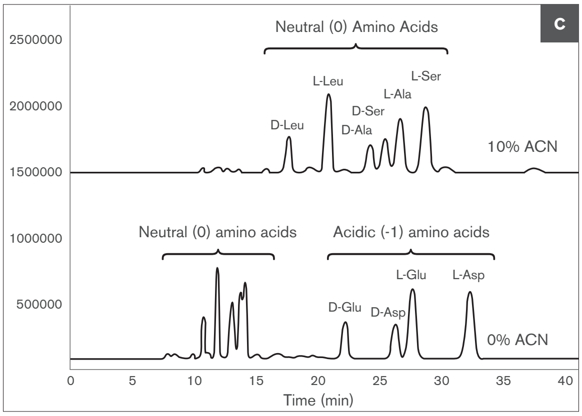

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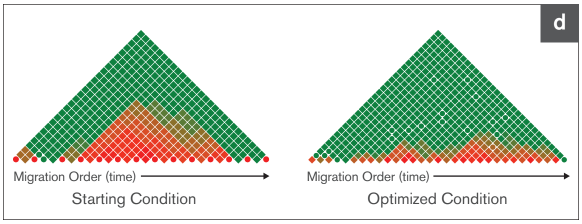


> "The leadership contributions from **JONAS ZMUIDZINAS** to MDL's success cannot be overstated."

INFRASTRUCTURE & CAPABILITIES

Core MDL capabilities are supported by members of the Central Processing and MDL Support Group. Rear Row: [L to R] Frank Greer, Bill Badboy, Mike Garcia, James Wishard, Mark Mandel. Front Row: [L to R] Toney Davis, Chuck Manning, James Lamb, Michael Martinez, Matt Dickie.

STRATEGIC INVESTMENT

THE FOUNDATION OF OUR TECHNICAL IMPLEMENTATION AND INNOVATION RELIES ON SOPHISTICATED NEW INSTRUMENTATION IN ULTRACLEAN, SAFE ENVIRONMENTS.

The leadership that allowed successful and significant research, development, and deliveries from JPL's Microdevices Laboratory (MDL) required sustained and insightful investments in the core capabilities of people, organization, infrastructure, and equipment. The initial visionary investment in MDL as the primary laboratory for the Center of Space Microelectronics Technology (CSMT) was spearheaded by the late JPL Director Dr. Lew Allen, who obtained funding for construction of the facility (1987), and was sustained through its early years by support from the next JPL Director, Dr. Ed Stone. During the early period, Jonas Zmuidzinas, as a Caltech Professor, benefited as a stakeholder from the detectors developed in MDL. The next JPL Director, Charles Elachi, together with advocacy from the newly appointed JPL Chief Technologist, Paul Dimotakis, continued to support MDL, and established it as a Center of Excellence in its own right. Jonas Zmuidzinas took on a leadership and an advocacy role at that time as the first Microdevices Laboratory Director, and established a fund for sustained annual equipment investments. This advocacy role for MDL continued when Jonas took on the role of the JPL Chief Technologist with Chris Webster appointed as the second MDL Director.

The vision of these leaders, the organizations set up by them, and the significant investments in creating MDL's infrastructure and fabrication equipment were the foundation upon which everything else was built. Of course, critical tooling is a necessary, but not sufficient, condition for a successful endeavor. This infrastructure and equipment also must be safe, reliable, and well-maintained, function optimally, and be continually renewed. The small specialized staff in the Central Processing and MDL Support Group helps to do this directly, as well as coordinating the expert efforts of other support groups both internal and external to JPL.

INFRASTRUCTURE

During the last decade under the leadership and advocacy of Jonas Zmuidzinas, significant and sustained investments were made to renew the building infrastructure. Major renewals/modernizations included cleanroom expansions; HEPA/ULPA filter replacements; safety monitoring equipment replacements; process cooling water system replacement/upgrades; compressed dry air system replacement/expansion/upgrades; and DI water plant upgrades.

In 2015, the major focus that involved facilities was the safe decontamination and removal/donation of the Thomas Swan Metal Organic Chemical Vapor Deposition (MOCVD) system with attendant Gaseous Hydrogen Distribution System source bunker decommissioning. Two other systems, an NRC Thermal Evaporator and a Brewer Scientific Spinner System, were also removed and surplused. Other minor infrastructure improvements/replacements to building systems included replacements of chemical storage refrigerators, overflow modification isolation to the inorganic exhaust wet scrubber, and updates to alarm sequencings.

EQUIPMENT

The last decade also saw insightful semiconductor processing equipment investments to renew, modernize, and add new capabilities to MDL's tool set, including the ability to process and handle larger (150-mm, 6-inch) diameter wafers. Significant multimillion-dollar equipment investments were made in the areas of patterning, deposition, etching, and characterization. Specific examples include the purchase and installation of two lithography steppers, two spinner systems, an 8-inch Si MBE, two ALD systems, four CVD systems, seven evaporator/sputtering systems, one additional deep silicon etcher, three ICP etchers, and seven major characterization equipment investments.

IN 2015, NEW INVESTMENT ACQUISITIONS INCLUDED:

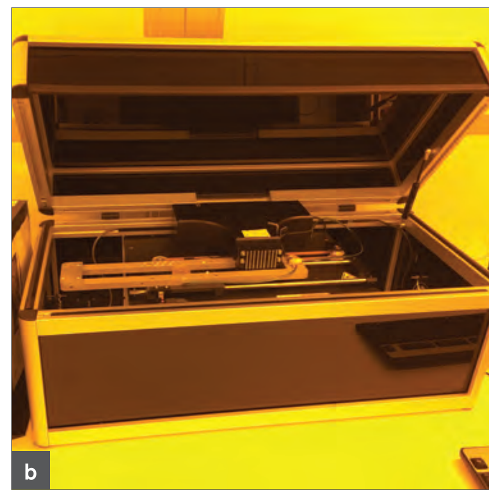
- Park Systems Inc. NX20 Atomic Force Microscope (AFM) system
- LEI 1510 Contactless Sheet Resistance Tool
- Novascan UV8 Ultraviolet Light Ozone Cleaner

Also, a new in situ ion mill capability was installed on the existing Load-locked AJA Electron Beam Evaporator, and a dedicated small RIE, oven, and hot plates were installed in the MDL Cleanroom Processing areas.

JPL management also authorized funding to purchase a replacement for the aging and existing JEOL JBX 9300FS Electron-Beam Lithography System. The system was specified, and a multimillion-dollar subcontract was issued for a JEOL JBX 9500FS Electron-Beam Lithography System. This system will take 18 months to construct, and 5 months to install and qualify. The system is expected to be fully qualified and operational at MDL in March 2017.

OUTREACH AND MARKETING

MDL's outreach and marketing activities were also continued. Updates to the first-floor display areas were completed. Over 80 tours (nom. 7/mo.) were given throughout the year. During the JPL Open House held on Saturday, October 10, 2015, and Sunday, October 11, 2015, 13,431 people were counted as physically entering and viewing the MDL displays, and 1,921 infrared camera photographs were printed and distributed to the public over these two days.



a ▪ Park Systems NX20 Atomic Force Microscope System. b ▪ LEI 1510 Contactless Sheet Resistance Tool. c ▪ Novascan UV8 Ultraviolet Light Ozone Cleaner.

APPENDICES | MDL EQUIPMENT COMPLEMENT

MATERIAL DEPOSITION

- Thermal Evaporators (5)
- Electron-Beam Evaporators (7)
- Angstrom Engineering Indium-metal Evaporator
- Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (3)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (3)
- AJA Load Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- PlasmaTherm 790 Plasma Enhanced Chemical Vapor Deposition (PECVD) for Dielectrics
- Oxford Plasmalab System 100 Advanced Inductively Coupled Plasma (ICP) 380 High-Density Plasma Enhanced Chemical Vapor Deposition (HD PECVD) System for Low-Temperature Dielectric Growths
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Beneq TFS-200 Atomic Layer Deposition (ALD) System
- Tystar (150mm /6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 2 Tubes for
    - Low-Stress Silicon Nitride
    - Atmospheric Wet/Dry Oxidation
- Carbon Nanotube Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
    - Veeco GEN200 (200mm/8-inch) Si MBE for UV CCD Delta Doping (Silicon)
    - Veeco Epi GEN III MBE (Antimonide Materials)
    - Riber MBE for UV CCD Delta Doping (Silicon)
    - Riber Device MBE (GaAs)

LITHOGRAPHIC PATTERNING

- Electron-Beam (E-beam) Lithography: JEOL JBX9300FS E-beam lithography system with a 4-nm spot size, 100,000 volt acceleration voltage, ability to handle wafers up to 9 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 7 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7-µm resolution)
- Canon FPA3000 i4 i-Line Stepper (0.35-µm resolution)
- Canon FPA3000 EX3 Stepper with EX4 Optics (0.25-µm resolution)
- Canon FPA3000 EX6 DUV Stepper (0.15-µm resolution)
- Contact Aligners:
    - Karl Suss MJB3
    - Karl Suss MJB3 with backside IR
    - Suss MA-6 (UV300) with MO Exposure Optics upgrade
    - Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
    - Suss Gamma 4 Module Cluster System
    - Site Services Spin Developer System
    - SolarSemi MC204 Microcluster Spin Coating System
- Yield Engineering System (YES) Reversal Oven
- Ovens, Hotplates, furnaces, and Manual Spinners (including 2 Solitec 5110C spinners, and a Suss RC8 Spin Coater)

DRY ETCHING

- Commonwealth IBE-80 Ion Mill
- Branson Plasma Ashers (2)
- Tepla PP300SA Microwave Plasma Asher

FLUORINE-BASED PLASMA ETCHING SYSTEMS

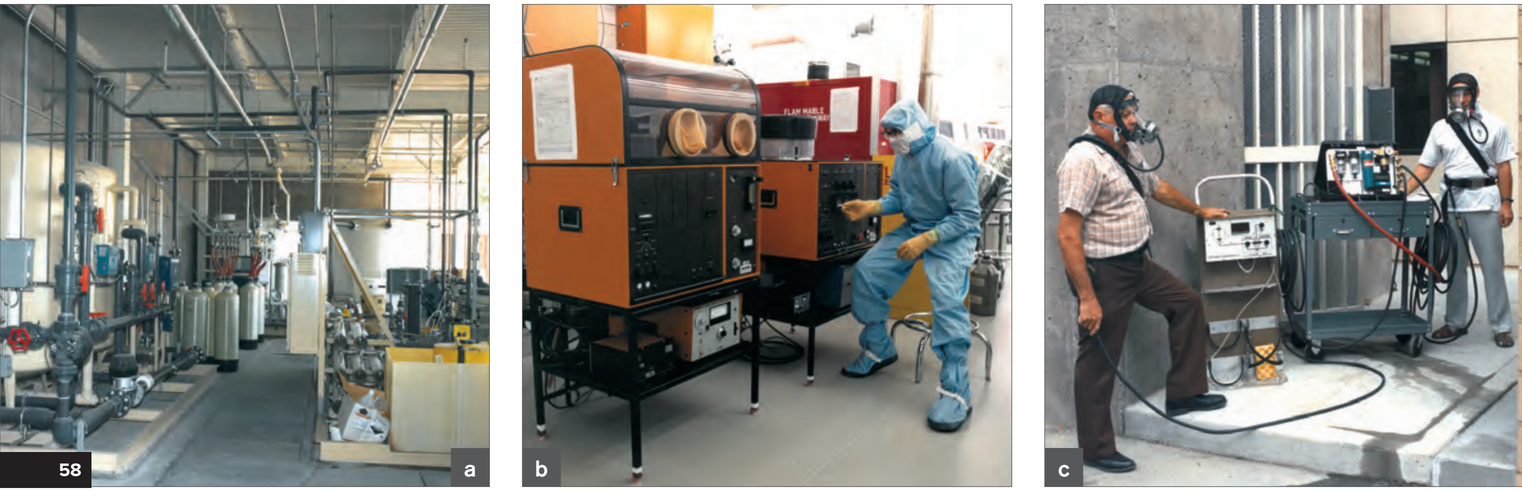
- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- PlasmaTherm Versaline Deep Silicon Etcher (DSE/DRIE)
- Unaxis Shuttleline Load-Locked Fluorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm APEX SLR Fluorine-based ICP RIE with Laser End Point Detector
- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 etcher

CHLORINE-BASED PLASMA ETCHING SYSTEMS

- Unaxis Shuttleline Load-Locked Chlorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm Versaline Chlorine-based ICP Etcher
- Oxford ICP Chlorine RIE

WET ETCHING & SAMPLE PREPARATION

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (7)
- Rinser/Dryers for Wafers including Semitool 870S Dual Spin Rinser Dryer



a | View of the MDL DI Water Plant when the building was first made operational in 1989. b | A member of the MDL Support Staff in cleanroom coveralls operates an etcher during initial system installation and qualification in the MDL cleanrooms in 1990. c | Past MDL Facilities Engineers Hugo Velasquez and Charles Radics wearing Self Contained Breathing Apparatuses (SCBAs) prepare to receive and install toxic gases in MDL's Hazardous Gas Bunker.

- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Tousimis 915B Critical Point Dryer
- Rapid Thermal Processors/Contact Alloyers (2)
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher
- Precitech Nanonform 250 Ultra Diamond Point Turning System
- SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool
- Novascan UV8 Ultraviolet Light Ozone Cleaner
- New Wave Research EzLaze 3 Laser Cutting System
- Indonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher

PACKAGING

- SET FC-300 Flip Chip Bump Bonder
- Karl Suss Wafer Bonder
- Electronic Visions Wafer Bonder
- Finetech Fineplacer 96 "Lambda" Bump Bonder
- Thinning Station and Inspection Systems for CCD Thinning
- Wire Bonding
- DISCO 320 and 321 Wafer Dicers (2)
- Tempress Scriber
- Pick and Place Blue Tape Dispenser System
- Loomis LSD-100 Scriber Breaker
- SCS Labcoater 2 (PDS 2010) Parylene Coating System

CHARACTERIZATION

- Profilometers (2) (Dektak 8 & Alphastep 500)
- Frontier Semiconductor FSM 128 Film Stress Measuring system
- Frontier Semiconductor FSM 128-NT (200mm/8-inch) Film Stress and Wafer Bow Mapping System
- LEI 1510 Contactless Sheet Resistance Tool
- FISBA μPhase 2 HR Compact Optical Interferometer
- Senetech SE 850 Multispectral Ellipsometer
- Horiba UVSEL 2 (190-2100 nm) Ellipsometer
- Dimension 5000 Atomic Force Microscope (AFM)
- Park Systems Inc. NX20 Atomic Force Microscope (AFM)
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- JEOL JSM-6700 Field Emission SEM with EDX
- Nikon & Zeiss Inspection Microscopes with Image Capture (3)
- Olympus LEXT 3D Confocal Microscope
- Electrical Probe Stations with Parameter Analyzers (2)
- RPM2035 Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectroscopy
- PANalytical X'Pert Pro MRD with DHS High Temperature Stage X-ray Diffraction System
- Surface Science SSX501 XPS with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- Nanometrics ECV Pro Profiler
- VEECO / WYKO NT 9300 Surface Profiler (including 50X optics)
- Zygo ZeMapper non-contact 3D Profiler

PEER-REVIEWED JOURNAL PUBLICATIONS

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2. N. Chahat, A. Tang, C. Lee, R. Sauleau, and G. Chattopadhyay, “Efficient CMOS Systems with Beam-Lead Interconnects for Space Instruments,” *IEEE Trans. THz Sci. Technol.*, 5 (4), 637 (2015).
3. D. Cunnane, J. H. Kawamura, M. A. Wolak, N. Acharya, T. Tan, X. X. Xi, and B. S. Karasik, “Characterization of MgB_2 Superconducting Hot Electron Bolometers,” *IEEE Trans. Appl. Supercond.,* 25(3), Pt. 1, 2300206 (2015).
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5. B. S. Karasik, C. B. McKitterick, T. Reck, and D. E. Prober, “Normal Metal Hot-Electron Nanobolometer with Johnson Noise Thermometry Readout,” *IEEE Trans. Thz Sci. Technol.*, 5 (1), 16 (2015).
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8. J. Hennessy, A.D. Jewell, F. Greer, M.C. Lee, S. Nikzad, “Atomic Layer Deposition of Magnesium Fluoride via Bis(ethylcyclopentadienyl)magnesium and Anhydrous Hydrogen Fluoride,” *J. Vac. Sci. Technol. A*, 33 (1), 01A125, (2015). Featured article as “Editor’s Picks” on JVSTA website.
9. J. Hennessy, A.D. Jewell, M.E. Hoenk, S. Nikzad, “Metal-Dielectric Filters for Solar-Blind Silicon Ultraviolet Detectors,” *Appl. Opt.*, 54 (11), 3507, (2015).
10. J. Hennessy, A.D. Jewell, K. Balasubramanian, S. Nikzad, “Ultraviolet Optical Properties of Aluminum Fluoride Thin Films Deposited by Atomic Layer Deposition,” *J. Vac. Sci. Technol. A* 34 (1), 01A120, (2016).
11. P. Suvarna, J. Bulmer, J. M. Leathersich, J. Marini, I. Mahaboob, J. Hennessy, L.D.Bell, S. Nikzad, F.(Shadi) Shahedipour-Sandvik, “Ion Implantation-Based Edge Termination to Improve III-N APD Reliability and Performance,” *IEEE Photonics Technol. Lett.* 27 (5), 498, (2015).
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NEW TECHNOLOGY REPORTS

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2. E. Sunada, K. Yee, S. Reilly, "Etched silicon biporous wick for high heat flux heat spreaders," NTR: 50082 (December, 2015).
3. T. Pagano, H. Aumann, S. Gunapala, C. Henegan, C. Henry, D. Johnson, J. Rodriquez, A. Kuhnert, K. Aaron, M. Lane, C. McKinney, M. Rud, K. Yee, "CubeSat Infrared Atmospheric Sounder (CIRAS)," NTR: 49984 (September, 2015).
4. H. Leduc, P. Day, L. Baker, B.H. Eom, and F. Greer, "ALD TiN/VN Process Development and Nanolaminates for Submillimeter Astronomy," NTR 49855, May 4, 2015.
5. S. Nikzad, B.C. Jacquot, T.J. Jones, M.R. Dickie, H.F. Greer, M.E. Hoenk, and E. Hamden, "Contact Shadow Masks to Enable Multiple Bands of ALD-Deposited Anti-Reflection Coatings," NPO 47647, September 29, 2015.
6. R. Kapadia, K. Ahmed, and F. Greer, "Heterojunction NIIP Photodetector," NTR 50083, January 19, 2016.
7. F. Greer, "Infinitely Selective Atomic Layer Deposition Utilizing Atomic Layer Etching," NTR 49749, (With no docket date as of 2/1/2016).
8. W. R. Johnson, D. W. Wilson, and A. Soibel, "All-Reflective Faceted Pupil Spectral Imager (FPSI)," CIT File No.: CIT-7415-P.
9. D. Z. Ting, A. Soibel, A. Khoshakhlagh, and S. D. Gunapala, "Enhanced quantum efficiency barrier infrared detectors," (NTR- 50078, 08- Dec-2015).
10. R.M. Briggs, C. Frez, and S. Forouhar, "Semiconductor quantum cascade lasers fabricated without epitaxial regrowth," NASA Tech Briefs, NPO-49037, November 2015.

PATENTS

1. H. Manohara, R. Toda, L. Del Castillo, R. Murthy, "Systems and Methods for Fabricating Carbon Nanotube-Based Vacuum Electronic Devices," U.S. Patent 9,093,242, Issued 07/28/15.
2. T.J. Cunningham, B.R. Hancock, C. Sun, T.J. Jones, M. R. Dickie, S. Nikzad, M.E. Hoenk, C.J. Wrigley, K.W. Newton, and B. Pain, "Sparsely – Bonded CMOS Hybrid Imager," US Patent No 9,105,548 B2, August 11, 2015.
3. M. Hoenk, F. Greer, and S. Nikzad, "Atomic Layer Deposition of High Performance Anti Reflection Coatings on Delta- Doped CCDs," US Patent No 9,123,622, September 1, 2015.
4. F. Greer, T. Jones, S. Nikzad, and M. Hoenk, "Atomically Precise Surface Engineering for Producing Imagers," US Patent No 9,165,971, October 20, 2015.
5. D. Z. Ting, C. J. Hill, A. Soibel, S. V. Bandara, and S. D. Gunapala, "High Operating Temperature Barrier Infrared Detector with Tailorable Cutoff Wavelength," U.S. Patent No. 8,928,036 B2, January 6, 2015.
6. D. Ting, A. Khoshakhlagh, C. Hill, S. Keo, A. Soibel, S. Gunapala, "Barrier Infrared Detectors on Lattice Mismatch Substrates," U.S. Patent No. 9,214,581, December 15, 2015.
7. R. M. Briggs, C. Frez, and S. Forouhar, "Index-coupled distributed feedback semiconductor quantum cascade lasers fabricated without epitaxial regrowth," US Patent Application No. 14/711,695 (2015).
8. C. Frez, C.E. Borgentun, R. M. Briggs, M. Bagheri, and S. Forouhar, "Single-mode, distributed feedback interband cascade lasers," US Patent Application No. 14/824,933 (2015).
9. D.C.Hoffman, J.P.C. Borgonia, R.P. Dillon, E.J.Suh, J.L. Mulder, P.B.Gardener, "Methods for fabricating gradient alloy articles with multi-functional properties." US Patent No.: US 9,101,979,B2, (Aug. 11, 2015).

BOOK CHAPTERS

1. S. Nikzad, A. D. Jewell, A. G. Carver, M. E. Hoenk, L.D. Bell, L. D.; Maki, J. N., "Digital Imaging for Planetary Exploration." In *Handbook of Digital Imaging*; Kriss, M., Ed.; Wiley: New York, 2015.
2. Nikzad et al. "UV-Based Imaging Technologies for Intraoperative Brain Mapping" In *Textbook of Neurophotonics and Brain Mapping*, Y. Chen and B. Kateb, Eds.; CRC Press, Taylor & Francis Group, 2016.

INVITED TALKS

1. L. D. Bell, "Interface Characterization using Ballistic Electron Emission Microscopy and Spectroscopy: Recent Results and Related Techniques," **Invited** speaker at *American Vacuum Society 62nd National Symposium*, San Jose, California, 2015.
2. S. Cheng, S. Nikzad, T. J. Jones, M. E. Hoenk, D. Brown, A. Jewell, P. Von Allmen, "Curved Focal Plane Array Inspired by Human Eye," **Invited** speaker at *12th Annual World Congress of Society for Brain Mapping and Therapeutics,* Los Angeles, California, 2015.

3. T. Goodsall, S. Nikzad, M. E. Hoenk, A. Carver, J. Gilbert, "Silicon Detectors For Low Energy Ionizing Radiation Detection," **Invited** speaker at *12th Annual World Congress of Society for Brain Mapping and Therapeutics,* Los Angeles, California, 2015.

4. S. Nikzad, "High Performance Solid State Detectors for Low Energy Neutral and Charged Particle Detection," **Invited** speaker at *Measurement Technique on Solar and Space Physics Conference,* Boulder, Colorado, 2015.

5. S. Nikzad, "Seeing the unseen: From Nebulae to Neurons," **Invited** seminar at the *Center for Imaging Science,* Rochester Institute of Technology, New York, 2015.

6. S. Nikzad, "New Frontiers in Medical Technologies," **Invited** speaker at *Special Seminar on Medical Engineering,* California Institute of Technology, Pasadena, 2015.

7. S. Nikzad, "Advanced Imaging Technologies for Astrophysics, Planetary, Medical and Commercial Applications," **Invited** speaker at the *American Physical Society, Four Corners Conference,* Tempe, Arizona, 2015.

8. S. D. Gunapala, D. Z. Ting, S. B. Rafol, A. Soibel, A. Khoshakhlagh, C. J. Hill, L. Höglund, S. A. Keo, J. K. Liu, J. M. Mumolo, E. M. Luong, A. Fisher, "Superlattice infrared photodetector research at the jet propulsion laboratory," *SPIE Optics + Photonics Conference,* San Diego, CA, **Invited** Presentation, August 2015.

9. S. D. Gunapala, S. B. Rafol, D. Z. Ting, A. Soibel, C. J. Hill, A. Khoshakhlagh, J. K. Liu, J. M. Mumolo, S. A. Keo, L. Höglund, E. M. Luong, "Modulation transfer function of infrared focal plane arrays," *SPIE Optics + Photonics Conference,* **Invited** Presentation, San Diego, CA, August 2015.

10. R. M. Briggs, M. D. Shaw, F. Marsili, A. D. Beyer, J. D. Cohen, S. Meenehan, and O. J. Painter, "Waveguide-integrated WSi-based superconducting nanowire single-photon detectors," *SPIE DSS Sensing Technology + Applications,* Baltimore, Maryland, April 20-24, 2015. **Invited**.

SPECIAL RECOGNITION

¤ **R. BRIGGS**, Voyager Award: For the development of novel low-power-consumption quantum cascade lasers for planetary science instruments.

¤ **S. FOROUHAR** and **R. BRIGGS**, Team Award: For the successful delivery and ground testing of the Combustion Product Monitor instrument.

¤ **M. HOENK**, Program Committee 2016, SPIE Astronomical Telescopes and Instruments – High Energy Detectors.

¤ **A. JEWELL**, Elected Board Member 2014-2016, Southern California Section of the American Chemical Society (SCALACS).

¤ **S. NIKZAD**

- Associate Editor, *Journal of Astronomical Telescopes, Instruments, and Systems.*
- Guest Editor, *Neurophotonics.*
- President 2014-2015, Society for Brain Mapping & Therapeutics (SBMT).
- Co-Chair and Co-Organizer, 12th Annual Congress of SBMT, Chair and organizer for eight sessions.
- Program Committee 2015, International Image Sensor Workshop.
- Program Committee 2016, SPIE Astronomical Telescopes and Instruments – Gamma Ray to UV Missions and Instruments.
- Invited Alumna, USC Alumni Spotlight.
- Featured Interview, *PLOS ONE.*

¤ **K. YEE**, *et al.* Team award: For exceptional performance in uniquely fabricating high contrast imaging masks delivered to WFIRST AFTA team (7/3/2015).

¤ **H. MANOHARA**, S. Y. Bae, R.J. Korniski, and H. Shahinian, Federal Laboratories Consortium award for outstanding technology: For the development of Multi-Angle, Rear-Viewing Endoscopic tool or 3D-MARVEL, which is a new surgical tool developed for minimally invasive neurosurgeries, August 2015.

¤ **S. GUNAPALA**, Fellow, Optical Society of America, April 10, 2015.

¤ **A. SOIBEL**, Discovery Award: For the extra commitment and effort in computerizing the test device characterization setup, June 2015.

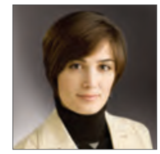
¤ **A. FISHER**, Discovery Award: For the extra commitment and effort in fabricating process evaluation chips, June 2015.

¤ **D. TING**, Voyager Award: For the breakthrough device design, which significantly enhanced the long-wavelength barrier infrared detector quantum efficiency, March 2015.

¤ **C. WEBSTER**, JPL Ed Stone Award for outstanding research paper 2016.

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 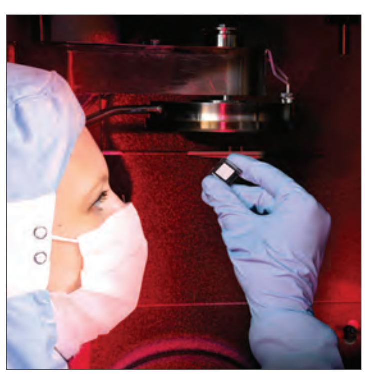 

The combination of the leadership, vision, and innovation of many dedicated and talented individuals at MDL, both past and present, has resulted in numerous achievements that are impressive for their scope, significance, and ingenuity. At the heart of this report's design is the intention to recognize and amplify the collaborative and additive process that made these achievements possible.

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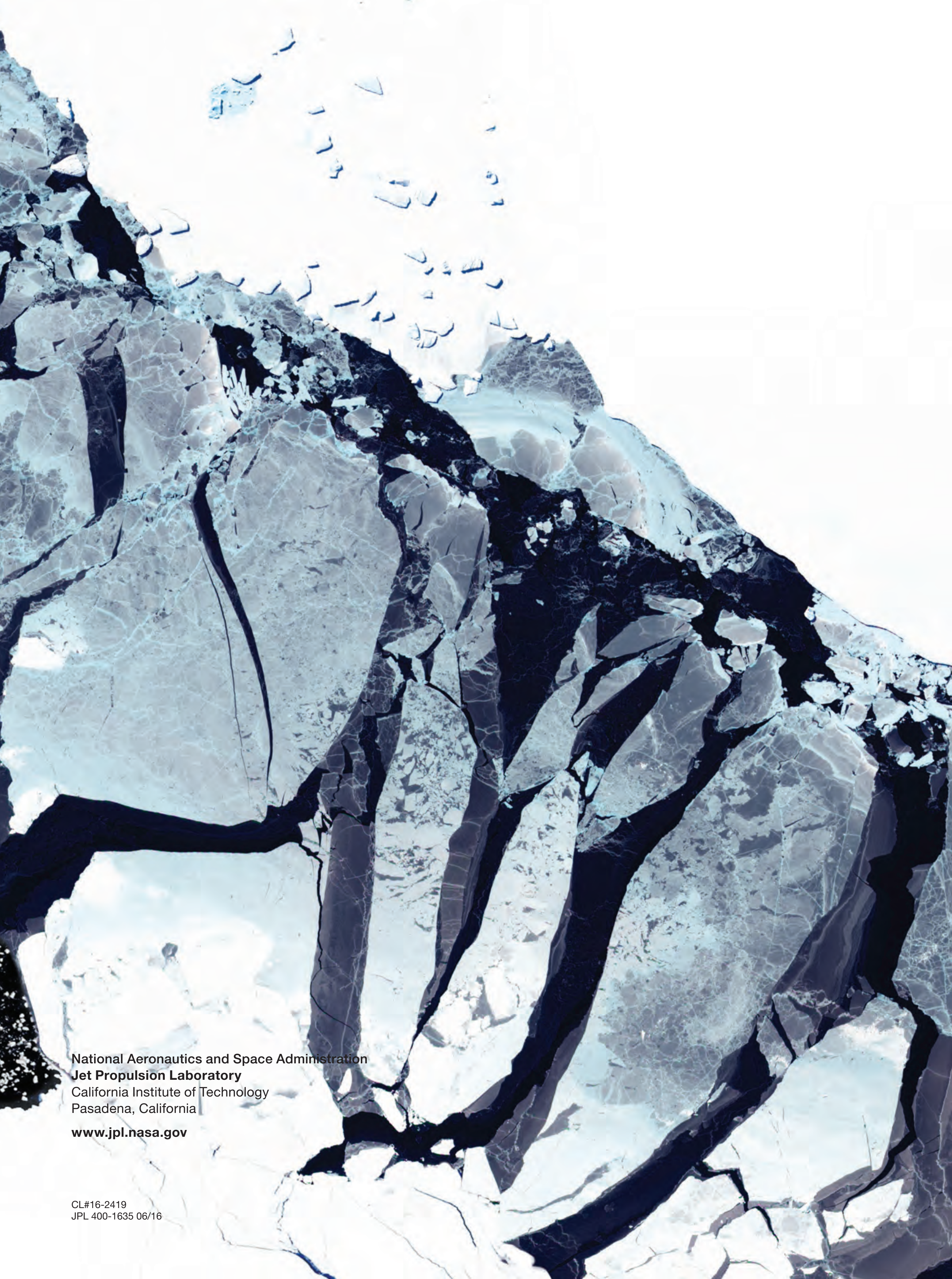

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