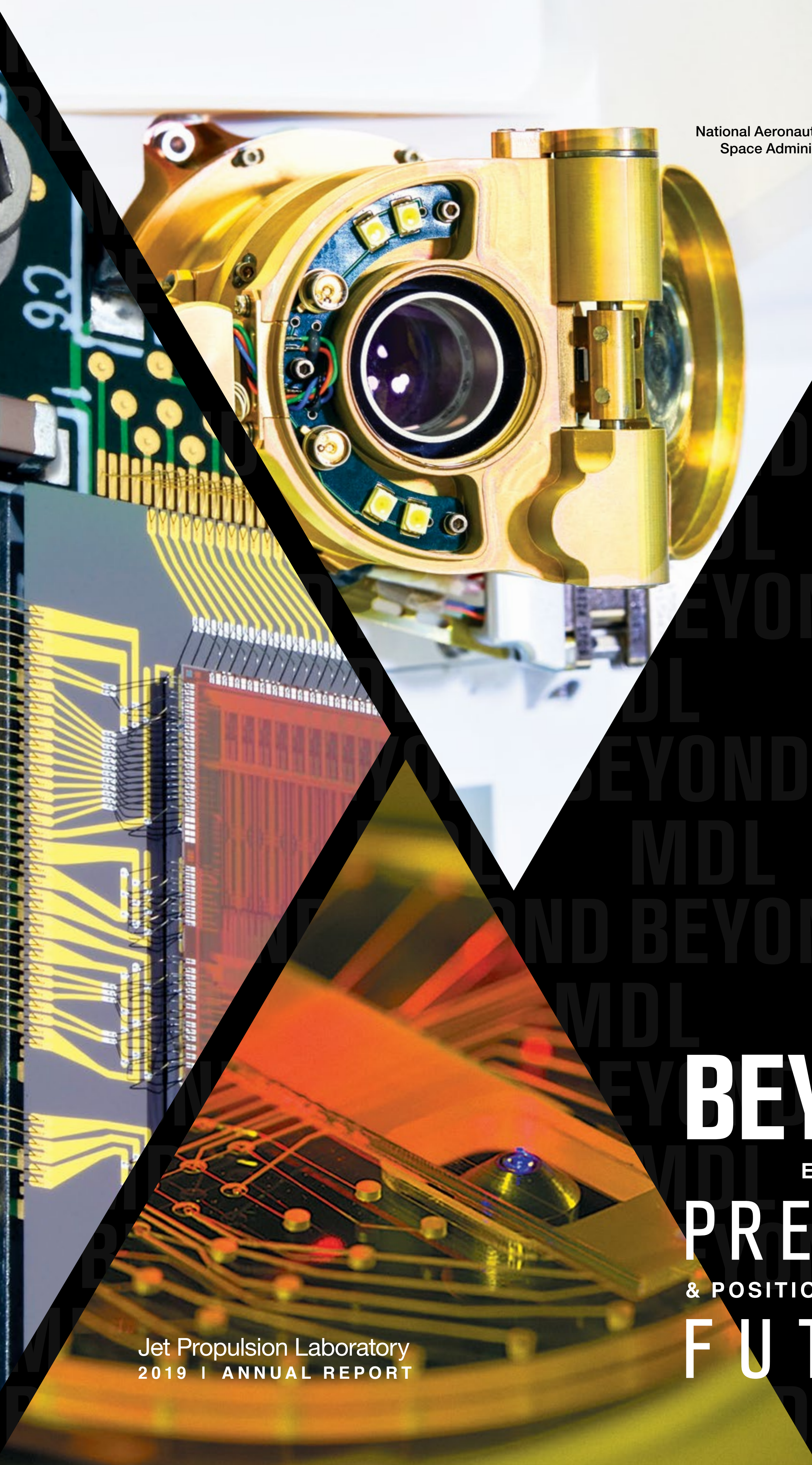


National Aeronautics and
Space Administration

MDL BEYOND

ENABLING THE
PRESENT
& POSITIONING FOR THE
FUTURE

Jet Propulsion Laboratory
2019 | ANNUAL REPORT

WHAT DRIVES MDL

NASA GOALS OBJECTIVES

NASA STRATEGIC PLAN

The plan emphasizes space exploration while affirming NASA's commitment to the advancement of science and aeronautics.

DISCOVER

Expand human knowledge through new scientific discoveries

UNDERSTAND the Sun, Earth, Solar System, and Universe

EXPLORE

Extend continuous human presence deeper into space and to the moon for sustainable long-term exploration and utilization

CONDUCT Human Exploration in Deep Space, including to the Surface of the Moon

DEVELOP

Address national challenges and catalyze economic growth

DEVELOP and TRANSFER Revolutionary Space Technologies to Enable Exploration Capabilities for NASA and the Nation

INSPIRE and ENGAGE the Public in Aeronautics, Space, and Science

ENABLE

Optimize capabilities

ENGAGE in Partnership Strategies

SUSTAIN Infrastructure Capabilities and Operations

NATIONAL STRATEGIC INPUT

NATIONAL ACADEMIES DECADAL SURVEYS

NASA relies on the science community to identify and prioritize leading-edge scientific questions and the observations required to answer them. One principal means by which NASA's Science Mission Directorate engages the science community in this task is through the National Research Council (NRC). The NRC conducts studies that provide a science community consensus on key questions posed by NASA and other U.S. government agencies.

NATIONAL SPACE COUNCIL NATIONAL SPACE POLICY

In 2017, President Trump reconstituted the National Space Council. The NSpC bridges the gap between the Executive Office, NASA, and commercial space activities. It establishes broad goals and objectives for the U.S. space program.

JPL STRATEGIC IMPLEMENTATION PLAN

STRATEGIC THEMES, PRIORITIES & GOALS

QUESTS

PURSUE a diverse and bold set of Science Missions

THRUSTS

CREATE the Laboratory of the Future

FUTURE CAPABIL-ITIES

ACCELERATE Technology Infusion

JPL STRATEGIC TECHNOLOGY DIRECTIONS

Strategic Technology Areas

MDL 2019 ANNUAL REPORT

Visit us at microdevices.jpl.nasa.gov

FOR NOW & TOMORROW Pg 10

This section of the report highlights some of the contributions MDL is making into current and near-future NASA missions that address fundamental scientific questions.

PREPARING FOR THE FUTURE Pg 26

Like the first section, this part describes inputs to NASA missions However, rather than being current or due to launch soon, the projects described in this section have a timeline further in the future.

MDL KEEPING AHEAD Pg 46

This final section gives examples of how MDL succeeds in its role in JPL and NASA and how it is managed to ensure it stays at the forefront. It also highlights MDL's contributions to society. This effort is guided by the JPL Strategic Implementation Plan 2018 and the JPL Strategic Technology Directions document, which indicates how JPL technology leadership will be necessary to deliver JPL Quests with missions in 2030-2035.

MDL BEYOND

ENABLING THE PRESENT & POSITIONING FOR THE FUTURE

The Jet Propulsion Laboratory's Microdevices Laboratory (MDL) has, since its inception in 1989, balanced two complementary roles. First, as part of JPL and the wider NASA community, MDL's scientists and technologists are fully aware of planned missions. Thus, they can make state-of-the-art contributions of instrument components or complete devices that will enable JPL and NASA to achieve the objectives of their current missions.

At the same time, MDL has a unique cadre of inventors who develop new approaches to device fabrication and new concepts for instruments. These contributions will make the missions of the future feasible. In short, MDL has been and will continue to enable the technology of the present and the future. These aspects of the MDL modus operandi are highlighted in the three sections of this report, which address the present, the future, and how MDL balances both.

JPL STRATEGIC IMPLEMENTATION PLAN

The previous pages show how MDL relates to the **JPL Strategic Implementation Plan 2018** (SIP), which in turn is guided by NASA and national policies. The chart below shows specifically how the activities highlighted in this report contribute to the SIP. Although it can be examined in detail, its aim is to convey the overall impression of the extent and multiplicity of ways in which this happens.

- MDL has on average just over 3 contributions to each of the first 6 **JPL Quests** and links across the board to the 7th Quest.
- The MDL contributions also relate very well to some of the **JPL Thrusts** and particularly to the **JPL Future Capabilities**

MDL CONTRIBUTIONS
TO THE JPL STRATEGIC IMPLEMENTATION PLAN

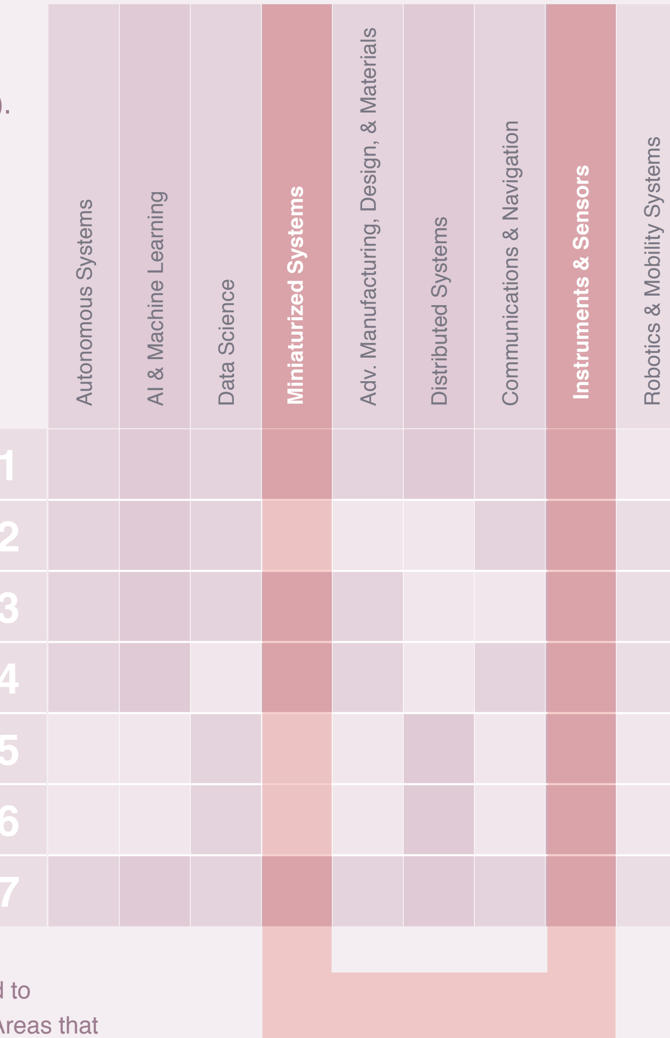
The Blue dots show liks to Section 1: Current and near-future projects and instruments.
The Salmon dots show links to Section 2: Future project and instrument opportunities.

JPL QUESTS		JWST	PIXL	SHERLOC	SAFFIRE	SAM	WI-ICOS	SEISMOMETER	WFIRST	PSYCHE	EUCLID	SPARCS	UCIS-MOON	PREFIRE	TIME	OWLS	HyTI
Understand how Earth works as a system and how it is changing	1						●	●					●	●		●	●
Help pave the way for human exploration of space	2				●	●											
Understand how our Solar System formed and how it is evolving	3		●	●				●		●							
Understand how life emerged on Earth and possibly elsewhere in our Solar System	4		●	●												●	
Understand the diversity of planetary systems in our Galaxy	5	●							●			●					
Understand how the Universe began and how it is evolving	6										●				●		
Use our unique expertise to benefit the nation and planet Earth	7	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
SELECTED FUTURE CAPABILITIES																	
Life Detection and Astrobiology	1	●	●	●					●			●				●	
SmallSats	2							●				●	●	●			●
In Situ Science	3		●	●			●	●					●			●	
Advanced Detectors	4				●	●		●	●	●	●	●	●	●	●		●

JPL STRATEGIC TECHNOLOGY DIRECTIONS

The **JPL Strategic Technology Directions** (StrTD) document was issued shortly after the **JPL Strategic Implementation Plan 2018** (JPL SIP). It shows specifically how **JPL Technology** leadership will be necessary to deliver the **JPL Quests** outlined in the SIP.

STRATEGIC TECHNOLOGY AREAS



JPL QUESTS

1. Understand how Earth works as a system and how it is changing
2. Help pave the way for human exploration of space
3. Understand how our Solar System formed and how it is evolving
4. Understand how life emerged on Earth and possibly elsewhere in our Solar System
5. Understand the diversity of planetary systems in our Galaxy
6. Understand how the Universe began and how it is evolving
7. Use our unique expertise to benefit the nation and planet Earth

Consultation with all potential stakeholders led to the identification of the Strategic Technology Areas that JPL must lead to be able to launch the missions that will fulfill the demands of the JPL Quests.

The preceding pages have shown how the MDL efforts described in this report support various objectives of the JPL SIP. Unsurprisingly, given MDL's track record, current efforts and competencies in the projects highlighted here align well with the topics in the StrTD.

Thus, the competencies are still relevant, and continuing effort will be needed to keep them at the forefront for missions 10 to 15 years in the future. Specifically, these efforts are crucial to two of the Strategic Technology Areas, **Miniaturization** and **Instruments and Sensors**.

MDL CONTRIBUTIONS
ARE AN ESSENTIAL PART OF TWO OF THE STRATEGIC TECHNOLOGY AREAS

SINCE OUR EARLIEST ANCESTORS LOOKED UP IN WONDER AT THE NIGHT SKY AND WONDERED 'HOW DOES THIS UNIVERSE WORK?' 'WHAT IS OUR PLACE IN IT?' AND 'ARE WE ALONE?', THESE MOST PROFOUND AND HUMAN QUESTIONS HAVE REALLY BEEN THE IMPETUS FOR HUMANITY'S JOURNEY OF EXPLORATION AND DISCOVERY. THE AMAZING THING IS THAT WE HAPPEN TO LIVE IN A TIME AND PLACE OF ALL THE GENERATIONS THAT HAVE LIVED ON THIS PLANET WHERE WE NOW HAVE THE TOOLS AND THE TECHNOLOGY – THE KNOWLEDGE – TO BEGIN TO ANSWER THESE QUESTIONS. NASA ITSELF AND OUR INTERNATIONAL PARTNERS IN SPACE EXPLORATION ARE IN FACT MOTIVATED BY THESE VERY SAME FUNDAMENTAL QUESTIONS.

– Douglas Terrier, NASA Chief Technologist

WE REALLY EXPLORE EVERYTHING FROM THE SURFACE OF THE EARTH TO THE EXTENT OF THE OBSERVABLE UNIVERSE... AND THEN AT THE EXTREMES OF THE UNIVERSE WE USE THE OBSERVATORIES WHERE WE WAIT FOR THE PHOTONS TO COME TO US AND GIVE A VIEW INTO THE VERY DISTANT PAST AND THE BEGINNING OF THE UNIVERSE.

– Douglas Terrier, NASA Chief Technologist

WHY WE CARE

LEADERSHIP FOREWORD

The Microdevices Laboratory (MDL), with its team of technologists, unique complement of fabrication equipment, and supporting facility continues to invent, develop, and qualify new devices to support NASA's mission of exploration and discovery.

Next-generation detectors are being developed for measurements ranging from soft X-rays to millimeter wavelengths. Superconducting nanowire single-photon detectors (SNSPDs) from MDL will be used to demonstrate deep space optical communication for NASA on the Psyche Discovery mission. At MDL, new types of micro-electro-mechanical systems (MEMS) seismometers are being developed with vastly reduced size, mass, and power requirements; these MEMS seismometers can enable new measurements and deployment scenarios for NASA in the future.

MDL remains committed to supporting the development of new devices and methodologies to detect life throughout the solar system and is home to the Ocean Worlds Life Surveyor (OWLS) project. In pursuing its charter, MDL emphasizes collaboration and partnership with other centers, universities, laboratories, and industry to deliver specialized space-qualified devices for NASA. Today more than 15 MDL devices are incorporated into current and near-term missions for NASA Directorates. These and other developments in MDL device technology developments are described in this annual report.

Building on this success and within the context of JPL's Strategic Implementation Plan, MDL is making investments in people, equipment, and technologies to enable new classes of devices that will support exceptional missions for NASA in the 2025 and 2035 timeframes.

This past year has been especially important for the Microdevices Laboratory as it transitioned successfully to a new organizational structure designed to strengthen its ability to deliver novel devices and device-related capabilities for JPL and NASA.

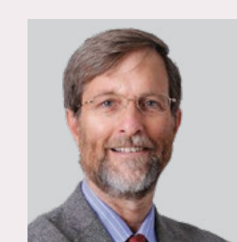
Simultaneously, and in concert with the JPL Chief Scientist and Chief Technologist, MDL has been delivering unique and enabling space-qualified devices for current and near-term instruments and missions to support NASA through the JPL Directorates of Solar System Exploration, Mars Exploration, Astronomy and Physics, Earth Science and Technology, and the Interplanetary Network.

MDL's refined organizational structure is optimized to support the exceptional scientists, technologists and support teams; the unique combination of device fabrication equipment; and the critical facility infrastructure that enable rapid concept development, fabrication, characterization, and space qualification of new devices. Within this structure, MDL holds a set of specialized competencies in the areas of mid-infrared detectors, UV-visible detectors, submillimeter devices, semiconductor lasers, superconducting devices, diffractive optics, broadband thermal detectors, micro-electro-mechanical systems, in situ instruments, tunable laser spectrometers, chemical analysis and life detection, mass spectrometry, and microfabrication technologies.

In the past year, MDL has strengthened its postdoctoral research program with a focus on inventing and developing next-generation devices beyond those currently conceived. Furthermore, we are pursuing opportunities to accelerate the infusion of new devices and technologies into missions while maintaining the rigor of appropriate space qualification.

This annual report and the updated MDL website (**microdevices.jpl.nasa.gov**) highlight our current activities and preparations to support JPL and NASA with new devices and capabilities for instruments and missions into the future.

MIKE WATKINS
Director,
Jet Propulsion Laboratory



ROBERT GREEN
Director,
Microdevices Laboratory

WHAT GUIDES MDL DIRECTIONS

JPL VISION STATEMENT

The **JPL Strategic Implementation Plan 2018** is significant because it lays out what JPL will do in the future and how it will be achieved.

The JPL Director, Michael Watkins, introduced the JPL Strategic Implementation Plan 2018 with a Vision Statement, which states in part, “To pursue our vision to ‘explore space in pursuit of scientific discoveries that benefit humanity,’ the JPL 2018 Strategic Implementation Plan responds to the NASA 2018 Strategic Plan and to the exciting new developments in the worlds of science, technology, and commercial space.”

“We will pursue our long-term scientific quests with a diverse and bold portfolio of missions as we push the limits of space exploration technology by developing and fielding ever more capable autonomous robotic systems.

“We will build a robust laboratory of the future that fosters a culture of innovation, openness, and inclusiveness, and we will transform our systems to promote easier collaboration and information sharing. How we conduct our business is as important to JPL, and to our ultimate success, as what we do. We also will continue to inspire the world through our stories and our journey into space.

“We will strengthen our end-to-end mission capabilities and accelerate the infusion of new technologies and capabilities into our future missions.”

The JPL Director notes that the JPL Strategic Implementation Plan 2018 responds to the NASA 2018 Strategic Plan. Likewise, this **MDL 2019 Annual Report** responds to the **JPL Strategic Implementation Plan 2018** and thus to the **NASA 2018 Strategic Plan**.

The JPL Strategic Implementation Plan is organized into three main sections:

JPL QUESTS

Long-term endeavors that support the JPL vision to “explore space in pursuit of scientific discoveries that benefit humanity.”

JPL THRUSTS

Cross-cutting initiatives designed to support our culture of innovation and the pursuit of our Quests.

FUTURE CAPABILITIES

Development and infusion of advanced technical capabilities into our future missions in pursuit of our Quests and in support of creating the laboratory of the future.

MDL CHARTER, ROLE & VISION

MDL is a JPL institutional facility chartered to **create**, **develop**, **deliver**, and **integrate** novel microdevices and critical microdevice technologies to **enable** or **enhance instruments** and missions that benefit **JPL** and **NASA**.

Based on its charter, MDL’s role and vision are to pioneer innovative and unique research and development in micro- and nanotechnology; provide world-class capabilities in the design, fabrication, and characterization of advanced components and sensors; and enable, develop, and support new and better instruments and mission capabilities at JPL, thereby providing enhanced science returns. The ultimate goal is to infuse and deliver the resulting MDL-developed technologies into projects of national interest.

Thus, MDL will directly enhance US competitiveness worldwide via NASA missions in astrophysics and planetary and Earth science; Department of Defense (DoD) space and terrestrial missions; and commercial applications in human health, environmental monitoring, and public safety.

The above scope is immense. Therefore, unsurprisingly, the work performed at MDL contributes to all three areas of the JPL 2018 Strategic Implementation Plan, and each section of this annual report contains examples of how MDL’s activities map directly onto the Plan. The three sections are:

01 FOR NOW & TOMORROW

02 PREPARING FOR THE FUTURE

03 MDL KEEPING AHEAD

The MDL way of working spans readiness for the immediately applicable to readiness for the germs of concepts for the far future, and all must be kept in balance to ensure a sustainable future.

MDL CONTRIBUTIONS TO HELP ACHIEVE THE JPL PLAN

As described in the **"MDL Charter, Role, and Vision"** section, each of the three sections of this report contains examples of MDL activities that contribute to or enable the objectives of the JPL Strategic Implementation Plan. These examples are just some of the highlights; a more comprehensive view can be found on the MDL website: **microdevices.jpl.nasa.gov**.

This section of the report highlights some of the contributions MDL is making into current and near-future NASA missions that address fundamental scientific questions.

Like section 1, this part describes inputs to NASA missions. However, rather than being current or due to launch soon, the projects described in this section have a timeline further in the future.

This final section gives examples of how MDL succeeds in its role in JPL and NASA and how it is managed to ensure it stays at the forefront. It also highlights MDL's contributions to society. This effort is guided by the JPL Strategic Implementation Plan 2018 and the JPL Strategic Technology Directions document, which indicates how JPL technology leadership will be necessary to deliver JPL Quests with missions in 2030-2035.

MDL BEYOND

Contents

SECTION 1

MDL BEYOND

FOR NOW AND TOMORROW

The **JPL Strategic Implementation Plan 2018 Quests** involve a continuing effort to fulfill the JPL vision to "**explore space in pursuit of scientific discoveries that benefit humanity.**" They relate directly to the goals and objectives of the **NASA Strategic Plan**, which embrace JPL's activities and how they are performed. These Quests are:

1. UNDERSTAND HOW EARTH WORKS AS A SYSTEM AND HOW IT IS CHANGING
2. HELP PAVE THE WAY FOR HUMAN EXPLORATION OF SPACE
3. UNDERSTAND HOW OUR SOLAR SYSTEM FORMED AND HOW IT IS EVOLVING
4. UNDERSTAND HOW LIFE EMERGED ON EARTH AND POSSIBLY ELSEWHERE IN OUR SOLAR SYSTEM
5. UNDERSTAND THE DIVERSITY OF PLANETARY SYSTEMS IN OUR GALAXY
6. UNDERSTAND HOW THE UNIVERSE BEGAN AND HOW IT IS EVOLVING
7. USE OUR UNIQUE EXPERTISE TO BENEFIT THE NATION AND PLANET EARTH

Thus, **JPL's Quests** underpin **NASA's vision.** In turn, MDL technology and processes underpin and, in some cases, enable these Quests. The following pages highlight the many technological and process contributions that MDL has made to these Quests.

JWST 12

Coronagraph: E-beam fabricated occulting spots for IRCam

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Spot-array generator gratings in Mars 2020 instrument

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E-beam fabricated ultraviolet grating for Mars 2020 instrument

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Combustion product monitor instrument for spacecraft fire safety demonstration tests

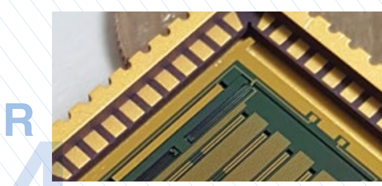
SAM 20

Micro-fabricated preconcentrator and gas chromatograph unit for ISS device

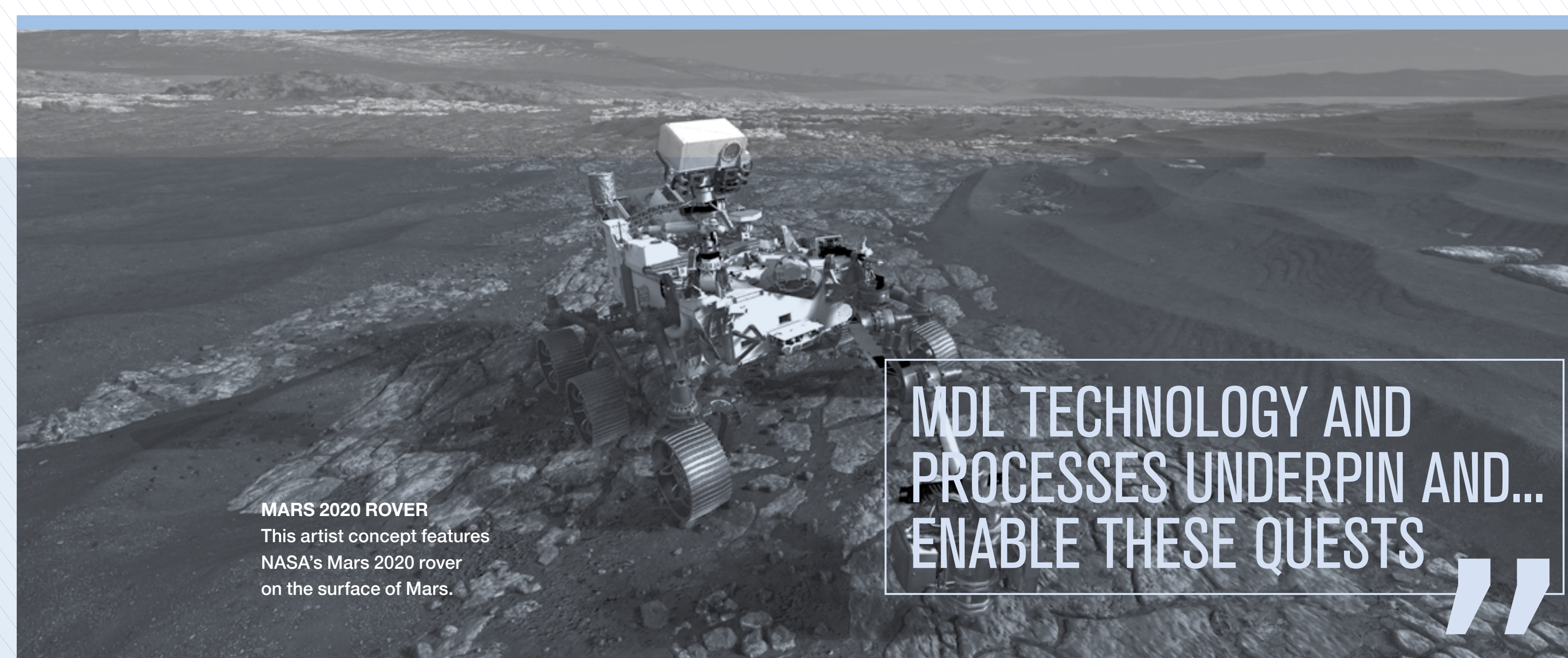
WI-ICOS 22

DFB-ICL (laser), thermoelectric cooler and lens for balloon mission instrument

SEISMOMETER 24



Universal MEMS Seismometer microdevice



MARS 2020 ROVER
This artist concept features NASA's Mars 2020 rover on the surface of Mars.

MDL TECHNOLOGY AND PROCESSES UNDERPIN AND... ENABLE THESE QUESTS"

MDL BEYOND JWST

JWST.
SP honeycomb mirrors make NASA's Webb the most powerful space telescope-RMB-3815.

> ENABLE DETECTION AND CHARACTERIZATION OF ORBITING EXOPLANETS"

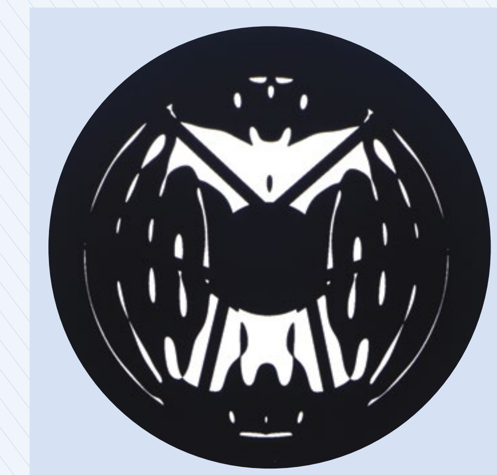
Flight Occulters

Shading a Lens from Bright Starlight

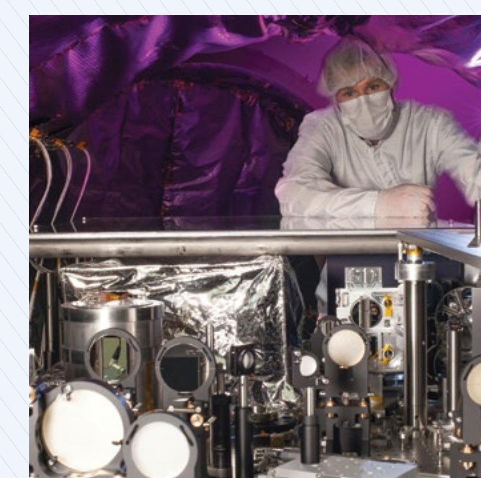
James Webb Space Telescope IRCam Coronagraph: E-beam fabricated occulting spots. An occulter is necessary to selectively shade a lens from bright starlight so that smaller, fainter objects can be imaged. Those on telescopes on Earth used to be very large and cumbersome. Special versions, called flight occulters, were developed for spaceflight.

MDL completed fabrication of five flight-occulting masks for the James Webb Space Telescope (JWST) Near Infrared Camera (NIRCam) coronagraph. These flight occulters enable detection and characterization of orbiting exoplanets. The occulters are binary half-tone patterns composed of near-wavelength-size holes and islands of thick aluminum, patterned by electron-beam lithography followed by plasma etching.

The half-tone patterns realize carefully designed Airy function apodizing masks that block the 2- to 5-µm wavelength starlight focused onto the occulter. The remaining light that passes through the NIRCam coronagraph is reimaged to enable detection and characterization of orbiting exoplanets.



BLACK SILICON MASK
A black silicon mask suppresses illumination from the host star to reveal light from an orbiting exoplanet that is up to a billion times fainter than that of the star.



VACUUM CHAMBER
A vacuum chamber is used for testing WFIRST and other coronagraphs. A star is simulated inside the chamber using light brought in by an optical fiber, and the light of this "star" is suppressed in the testbed by coronagraph masks and deformable mirrors.

> ELEMENT CHEMISTRY AT SUBMILLIMETER SCALES

Mars Rocks' Composition

Chemical Maps of a Planetary Surface

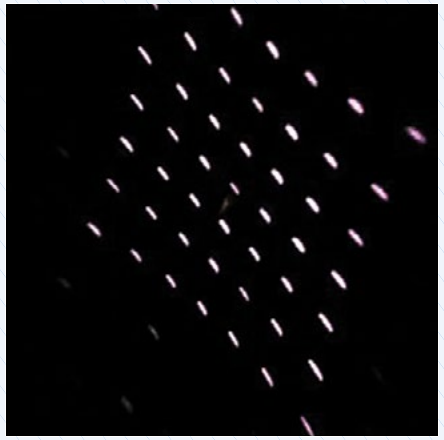
The Planetary Instrument for X-ray Lithochemistry (PIXL) for the Mars 2020 rover is an X-ray fluorescence instrument that rapidly measures elemental chemistry at sub-millimeter scales by focusing an X-ray beam onto a tiny spot on the target rock or soil and analyzing the induced X-ray fluorescence.

The PIXL Optical Fiducial Subsystem (OFS) uses two structured light illuminators with a camera system to localize the instrument relative to the sample and to map the topography of the surrounding area.

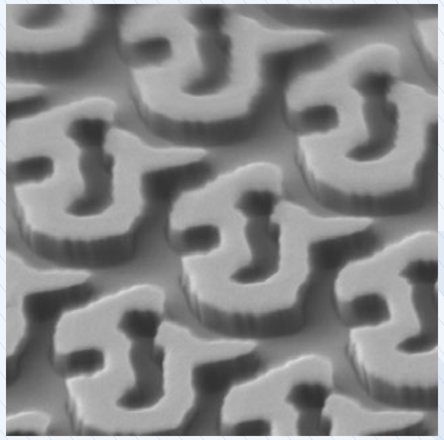
Critical to the OFS operation are diffractive spot array generators that produce 3x5 and 7x7 patterns of laser spots. The spot array generators are transmissive two-dimensional computer-generated hologram (CGH) gratings that are designed, electron-beam patterned, and plasma etched into fused silica substrates in MDL and were delivered in 2018. The photos at right show the design and microscope image of the fabricated 7x7 CGH.

Each cell of the CGH grating is made up of 160-nm square pixels and when etched to the proper depth in fused silica, the surface relief imparts a phase pattern on the laser beam (830 nm wavelength), causing it to diffract into 7x7 spots with nearly equal intensity.

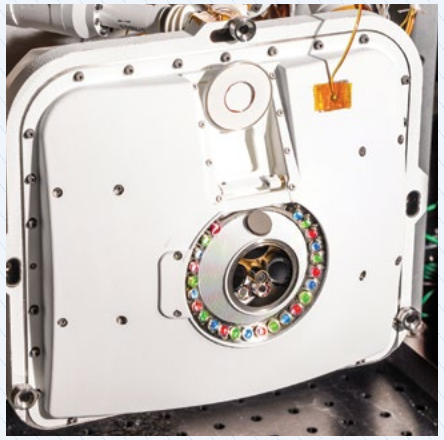
Gratings for 3x5 and 7x7 spot arrays have been fabricated, and two of each type were delivered to the project. They have been mounted in the OFS and successfully tested.



SPOT ARRAY. Seven-by-seven spot array produced by 830-nm infrared laser transmitted through the below CGH grating.



SEM OF GRATING. Scanning electron microscope (SEM) image of the seven-by-seven spot array grating.

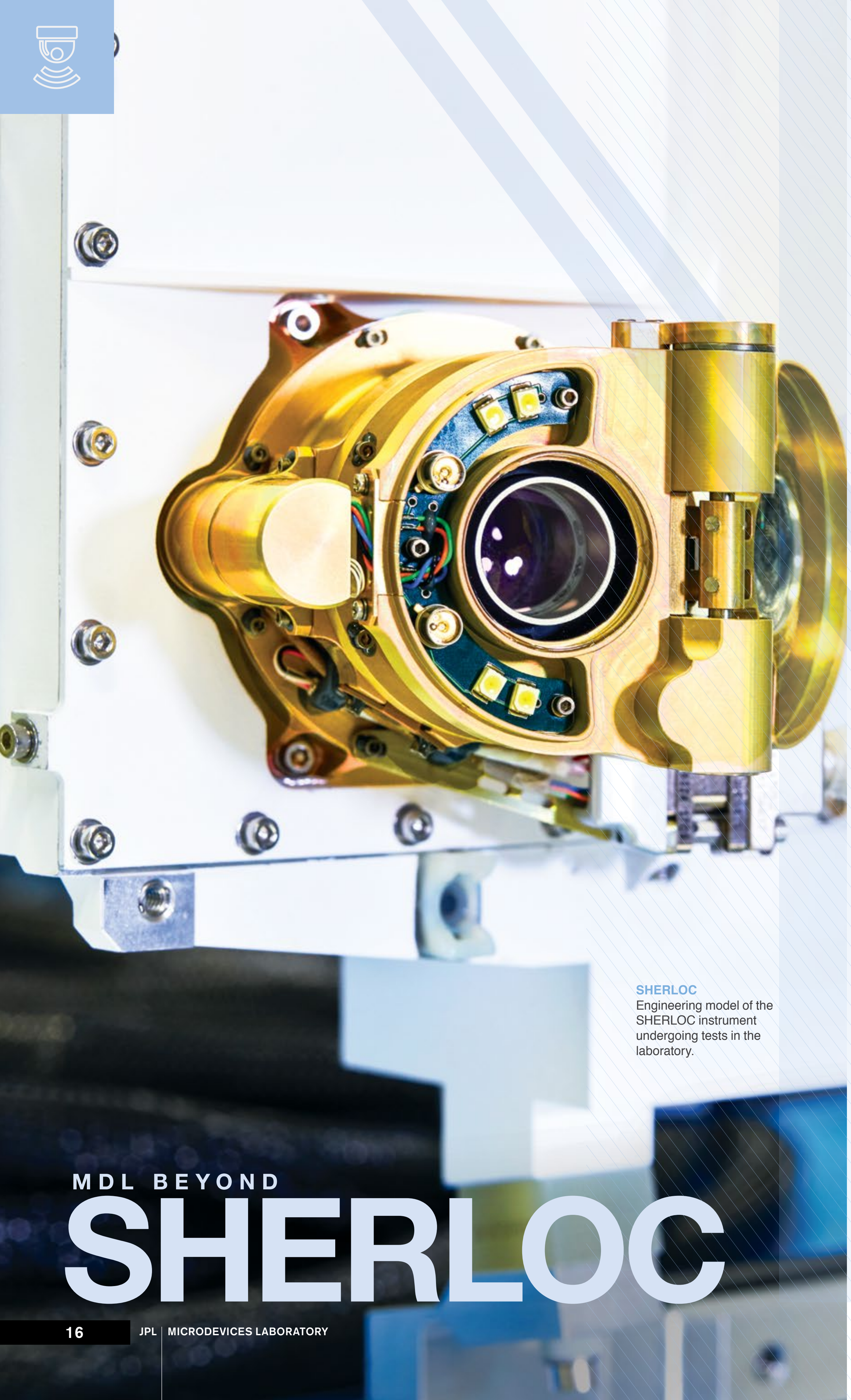


PIXL instrument engineering model in test.

Led by JPL, Mars 2020 takes the next step in NASA's Mars Exploration Program, probing the Martian rocks for evidence of past life. The four goals of Mars 2020 are to identify past environments capable of supporting microbial life, seek signs of biosignatures for past microbial life in those habitable environments, collect core rock and "soil" samples and store them on the Martian surface, and test oxygen production from the Martian atmosphere.

MDL BEYOND

PIXL



SHERLOC
Engineering model of the SHERLOC instrument undergoing tests in the laboratory.

FOR NOW & TOMORROW

DETECTION AND CHARACTERIZATION OF ORGANICS AND MINERALS IN THE MARTIAN SURFACE"

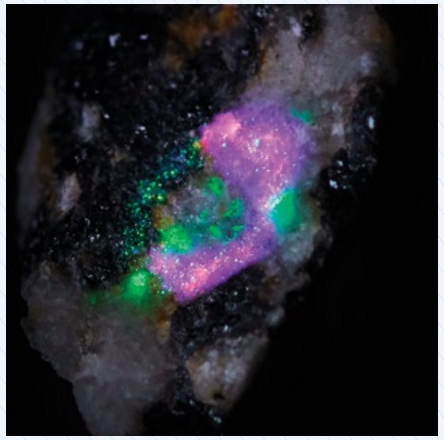
Looking for Life

Sensitive Analysis with UV Light

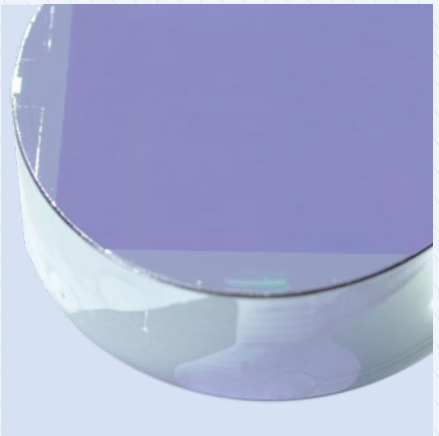
The Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) is an arm-mounted, deep UV (DUV) resonance Raman and fluorescence spectrometer utilizing a 248.6-nm DUV laser and <100 micron spot size.

SHERLOC enables non-contact, spatially resolved, highly sensitive detection and characterization of organics and minerals on the Martian surface and in the near subsurface.

The instrument goals are to assess past aqueous history, detect the presence and preservation of potential biosignatures, as well as to support selection of return samples. In support of SHERLOC, MDL has electron-beam-fabricated gratings for the Raman and fluorescence spectrometer. The grating has a very fine pitch, on the order of 200 nm, and the cross-section of the grooves is square, not sinusoidal. The gratings have demonstrated near-theoretical maximum diffraction efficiency at the 248.6 nm operating wavelength. Flight gratings have been fabricated, delivered and successfully tested.



SHERLOC
Image taken by the SHERLOC instrument of a test target showing the variation of composition across the sample.



E-BEAM GRATING
E-beam fabricated ultraviolet grating for Mars 2020 SHERLOC.

Space Fire Watch

Laser-based Instrument for Combustion Product Monitoring

Fires can happen anywhere—even in space. So, for the astronauts who live and work there, it is critical to understand how fire spreads in a microgravity environment and how to manage it safely. NASA has conducted studies as part of the space shuttle and International Space Station (ISS) programs, but they have been limited in size and scope due to the risks involved for astronauts. Now, new experiments are helping researchers better understand spacecraft fires on a larger scale.

The Spacecraft Fire Safety Experiment, known as Saffire, is a series of tests on unmanned supply vehicles returning from the ISS. MDL is developing a laser-based instrument to measure the gases that the test fires produce. Fire experiments in realistic environments help engineers understand risks to human health and formulate protective measures. Fire hazards are particularly dangerous in the confines of human-occupied spacecraft, yet there are limited opportunities to test fire protection systems in orbit.

Led by NASA's Glenn Research Center, the Spacecraft Fire Safety Experiment, also called Saffire, consists of a series of full-scale combustion tests performed aboard automated transfer vehicles during the return trip from the ISS. Saffire enables the study of flame growth, flammability limits, and other important characteristics within the unique low-gravity environment of space, without risking the safety of astronauts.

In 2019, engineers from MDL delivered the Combustion Product Monitor (CPM) instrument to measure specific fire products during a future Saffire flight. CPM uses compact semiconductor lasers to probe the abundance of carbon monoxide, carbon dioxide, and oxygen, as well as trace amounts of hydrogen fluoride, hydrogen chloride, and hydrogen cyanide, as these gases are produced (or consumed) during a combustion event. The instrument builds upon novel technologies in lasers, electronics, and optical design that have been developed at JPL for trace gas sensing in Earth and planetary science. The JPL CPM instrument is expected to launch aboard an Orbital Sciences Cygnus resupply vehicle in 2020. Fire experiments will be conducted after the spacecraft departs from the ISS and prior to reentering Earth's atmosphere.

In addition to supporting the near-term objectives of Saffire, the CPM instrument is a valuable testbed for laser spectroscopy sensors designed to support human spaceflight operations. Laser-based gas sensors can produce accurate concentration measurements over a broad range of pressures and temperatures and are capable of thousands of hours of maintenance-free operation. Such a robust sensor platform will be essential as humans push beyond low Earth orbit to explore deep space.

The Saffire program is led by Dr. Gary Ruff at the NASA Glenn Research Center in Cleveland, Ohio. The Combustion Product Monitor project at JPL is led by MDL's Ryan Briggs.

CPM
The completed combustion-product-monitoring instrument.

CYGNUS
Orbital supply vehicle.

> FIRE HAZARDS ARE PARTICULARLY DANGEROUS IN THE CONFINES OF HUMAN-OCCUPIED SPACECRAFT

Recent years have witnessed significant progress in the miniaturization of mass spectrometers for a variety of field applications. The main focus at JPL is on the two most common space-related applications of mass spectrometers: studying the composition of planetary atmospheres and monitoring air quality on manned space missions. JPL's miniature quadrupole ion trap mass spectrometer product has been under development for human space flight applications since 2003 and for planetary applications since 2011. NASA has made a significant commitment to this measurement technology upon which astronaut lives depend. This technology and its precision, mass, power, and robustness will benefit both human exploration and planetary science.

> MONITORING THE ATMOSPHERE OF CREWED SPACECRAFT "

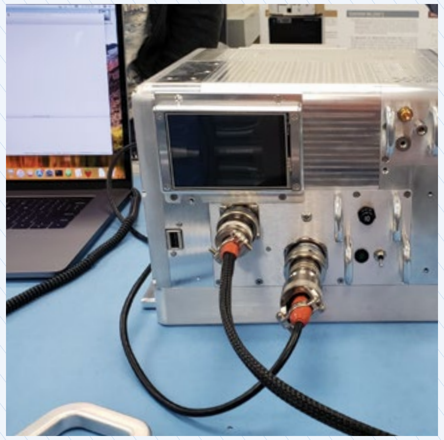
MDL BEYOND

SAM

A scanning electron microscope image of the cross-sectional view of the gas chromatograph serpentine channel.

Spacecraft Atmosphere

Next-generation Gas Chromatograph Mass Spectrometers



SAM instrument in the lab.

MDLhas been developing a micro-electro-mechanical system (MEMS) gas chromatograph that is a crucial part of JPL's Spacecraft Atmosphere Monitor (SAM). The SAM instrument is a highly miniaturized gas chromatograph/mass spectrometer (GC-MS) for monitoring the atmosphere of crewed spacecraft for both trace organic compounds and the major constituents of the cabin air. The SAM instrument, scheduled for launch to the International Space Station (ISS) in 2019, is the next generation of GC-MS, based on JPL's Vehicle Cabin Air Monitor (VCAM). VCAM was launched to the ISS in April 2010 and successfully operated for two years.

SAM consists of a miniature quadrupole ion trap mass spectrometer interfaced with a micro-fabricated preconcentrator and gas chromatograph unit (together forming the PCGC subassembly) and a small gas carrier reservoir. The micro-fabricated PCGC unit employs a novel MEMS PCGC technology that is implemented here by combining a MEMS preconcentrator, a microvalve and gas chromatograph chips that replace the macro PCGC components in the VCAM. This significantly reduces the total volume and mass of the gas chromatograph/mass spectrometer instrument from 64.4 L and 37.9 kg (VCAM) to 10 L and 9.5 kg (SAM).

The preconcentrator consists of a silicon-doped heater and a Carboxen layer in the chamber. The heater can be flash heated to 250°C in 0.5 seconds due to the thermally isolated design and material of the heater, which are made possible by through-etching around the heating plate and a silicon insulator, respectively. The JPL preconcentrator demonstrated more than a 10,000-fold concentration increase for alcohols, which is high enough for analysis of parts per billion concentrations of volatile organic compounds.

The electrostatically operated microvalve is composed of three main components: the top cap (TCAP)/valve closing (VC), the membrane, and the valve opening (VO)/ bottom cap (BCAP). The VC/TCAP and VO/BCAP are bonded as a stack using gold diffusion bonding technology. The VC/TCAP and VO/BCAP stack sandwich are bonded to the membrane layer using benzocyclobutene adhesive to complete the microvalve assembly. The membrane layer has four membranes embedded, each of which independently moves up and down in response to an applied electric field between the stacks.

These are the first electrostatic MEMS valves to achieve more than a million cycles. In fact, they achieved 47 million cycles before failure, which is equivalent to 5.9 years of operation when the valve is switched every four seconds. Other unique features include a center pad to reduce opening voltage and charge buildup; a pressure-balancing mechanism to lower differential pressure across the membrane, lowering stress and allowing the valve to open against high pressure; and an interface treatment to prevent charge buildup, which is the main failure mode of most other electrostatic valves.

The gas chromatograph microcolumn was completed in 2018. It is composed of multiple stacks of a 1-m serpentine column and a capping layer, which are hermetically sealed by metal diffusion or direct fusion bonding. The serpentine channel generates better separation than does a spiral channel design at the micro level of the chip's design. Silicon-silicon layers of the microcolumn deliver less tailing and peak broadening than conventional silicon-Pyrex microcolumns due to the higher uniform temperature profile. A cross-sectional scanning electron microscope image of the bonded serpentine channel is to the left. The gas chromatograph microcolumn also has a uniform self-assembly monolayer coating along the wall of the serpentine channel, which is facilitated by unique coating methodology.

MDL BEYOND
WI-ICOS

Water Isotopologues

Instrument on the Dynamics and Chemistry of the Summer Stratosphere Mission

In order to understand the processes that control regional precipitation and aridity, as well as the processes that control the humidity of the upper troposphere and lower stratosphere, it is necessary to track the movement of water in the atmosphere. One of the many powerful tools used is analysis of the isotopic composition of water in various air masses – the changes in the proportions of naturally occurring stable isotopes such as hydrogen (^{1}H) and deuterium (^{2}H) and oxygen (^{16}O and ^{18}O).

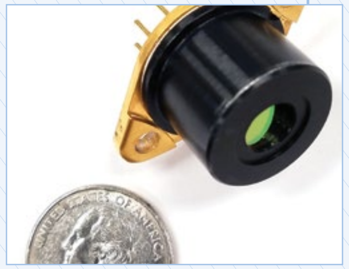
Changes in isotopic ratios reflect the history of phase changes—condensation, precipitation, evaporation—in water vapor. This work evolved from an earlier project as part of a longstanding, continuing partnership with Harvard University (see Section 3, page 62). Under the NASA Advanced Component Technologies Program, MDL developed a specialized laser that Harvard flew on a NASA high-altitude research balloon. This was part of the NASA Undergraduate Student Instrument Project (USIP) program; it was a DFB- ICL (Distributed-Feedback Interband Cascade Laser), packaged with a thermoelectric cooler and integrated lens to produce a collimated beam in the 3.3-micron region.

Harvard will also be flying JPL-produced lasers as part of the Water Isotopologues—Integrated Cavity Output Spectrometer (WI-ICOS) instrument on the Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) mission that was selected as part of the 2017 NASA Earth Venture Suborbital-3 solicitation. These lasers will measure total water vapor, including water isotopologues, in the upper troposphere and lower stratosphere on NASA's ER-2 research aircraft. The high power and integrated lens packaging design of these lasers in the 2.7-µm wavelength region represent a key advancement compared to commercially available state of the art and are essential to facilitating WI-ICOS's high-sensitivity approach to absorption spectroscopy.

NASA'S ER-2 RESEARCH AIRCRAFT Instrument flies in the mid-body of the ER-2 superpod.

LASER AND OPTICS are sealed in a pressure vessel and integrated into the WI-ICOS instrument .

LASER PACKAGE integrated into optical train leading to the hi-finesse optical cavity.



MDL LASER, TEC, and collimating optic packaged in TO-3 can.

NASA's high-altitude balloon being filled. The NASA USIP-funded mission balloon reached an altitude of 65,000 feet and then valved down slowly to the tropopause.

“DESIGNED TO OPERATE IN EXTREME ENVIRONMENTS

MDL BEYOND

SEISMO

InSight
InSight's self-portrait as a virtual-reality panorama.

MEMS Seismometer

Probing the Interiors of Extraterrestrial Planets

Seismology can most efficiently reveal the detailed structures of planetary interiors. Previous NASA missions that have carried seismometers as payloads include the Apollo moon missions and the Viking Mars landers. The InSight mission, launched in 2018, will utilize seismometers to learn about the interior of Mars.

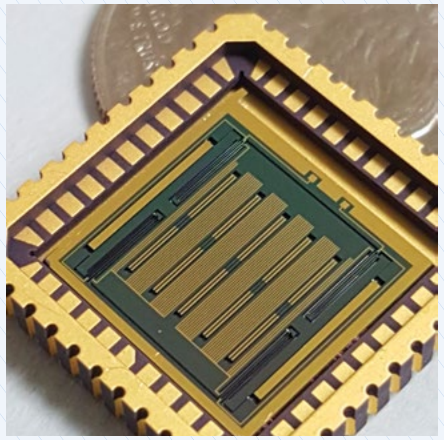
In the coming years and decades, NASA will launch a series of missions to explore our Moon and the ocean worlds of the solar system (e.g., Titan, Enceladus, Europa and Ganymede). Seismometers on such bodies would enable the determination of the interior, mantle and core structures, the characterization of fluid-flow-induced seismic activity, cryo-volcanic activity, and the frequency of meteoric impacts.

The Universal MEMS Seismometer (UMS)

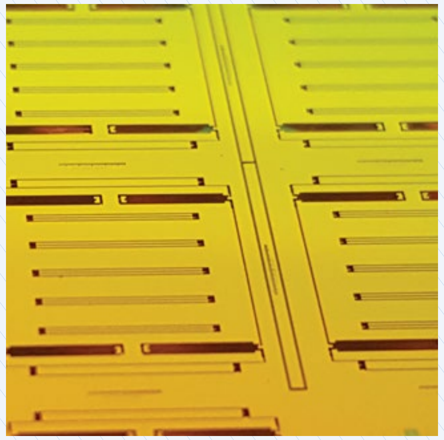
Traditional seismometers (such as those utilized on previous NASA missions) rely upon a large proof mass and soft suspension system for sensitivity. They tend to be large, fragile, and complex, requiring a dedicated soft lander, a deployment mechanism, leveling and environmental shielding. A sensitive and robust micro-seismometer that enables the science of traditionally larger, more complex seismometers, that can operate in any lander (or penetrometer) architecture, and that does not require leveling or environmental controls is therefore of the utmost strategic importance for NASA's future exploration of our solar system's ocean worlds.

Measuring only 11.3 x 11.3 and 1.2 mm, the Universal MEMS Seismometer (UMS) under development at MDL is a high-shock-tolerant micro seismometer that also has high performance (i.e., low noise, broadband and high dynamic range), enabled by the novel utilization of electrostatic spring softening. The UMS is designed to operate in the extreme environments (i.e., extreme temperatures, high radiation, large magnetic fields) of the Solar System's ocean worlds and rocky planets and will be easily incorporated into any lander architecture with negligible impact to spacecraft system weight and power and with no dependence on the deployment and leveling mechanisms required by most sensitive seismometers. Its high shock tolerance will also enable deployment via rough landers and penetrators, thus enabling for the first time the deployment of a network of seismometers on an extraterrestrial body.

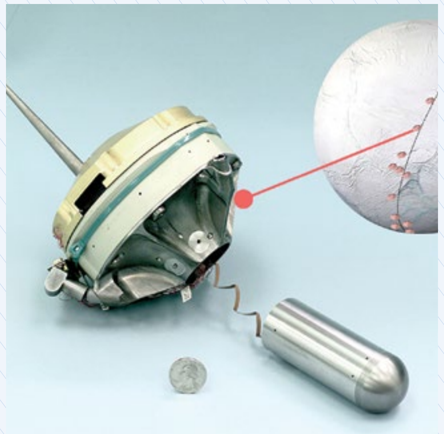
MEMS SEISMOMETER
Universal micro-electro-mechanical systems (MEMS) Seismometer mounted in vacuum package.



UMS SENSOR
Batch fabricated UMS sensors.



SEISMIC SENSOR
Concept for deployment of a network of seismic sensors using penetrator spacecraft.



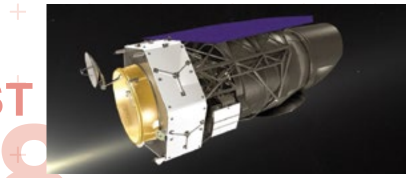
SECTION 2

MDL BEYOND

PREPARING FOR THE FUTURE

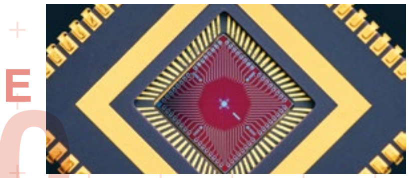
Like Section 1, Section 2 describes links to the **JPL Quests** identified in the **JPL Strategic Implementation Plan 2018.** The MDL efforts that have contributed to these missions are highlighted, as are the ways in which they address the fundamental scientific questions that NASA aims to answer. However, rather than being current or due to launch soon, the projects described in this section have a timeline further in the future.

WFIRST 28



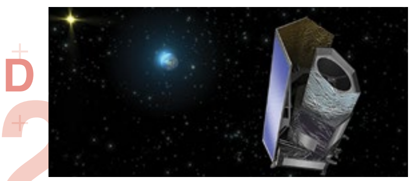
Masks for two different coronagraph types for a space telescope

PSYCHE 30



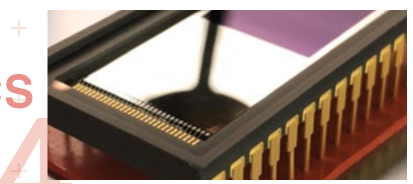
Superconducting nanowire single photon detectors for optical communication

EUCLID 32



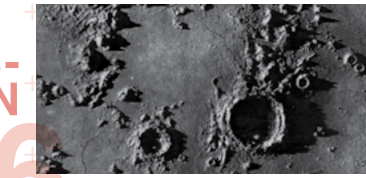
Silicon fan-out boards for the ASIC for ESA's Euclid space telescope

SPARCS 34



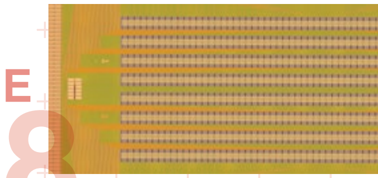
High-efficiency silicon UV detectors for the CubeSat space telescope

UCIS-MOON 36



Ultra-compact imaging spectrometer instrument for future lunar surface missions

PREFIRE 38

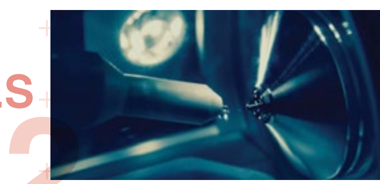


Thermopile detector array in CubeSat infrared instrument for Earth atmosphere data

TIME 40

TES bolometer array for a mm-wavelength grating spectrometer

OWLS 42



Electrochemical sensors and other parts of a life-detection instrument

HyTI 44

Next generation of thermal infrared imagers for low Earth orbit

MDL BEYOND WFIRST

“POTENTIAL PLANETARY BIRTHPLACES —IN OTHER STAR SYSTEMS

Most exoplanets have been detected indirectly by measuring their gravitational tug on their host stars or by sensing the dip in brightness of that star as the planet transits our line of sight. The Wide-Field Infrared Survey Telescope (WFIRST) is the first NASA space telescope designed to directly image and characterize exoplanets, as well as debris disks—potential planetary birthplaces —in other star systems.

WFIRST
An illustration of NASA's Wide-Field Infrared Survey Telescope.

First Exoplanetary Light

Space Telescope to Image and Characterize Exoplanets

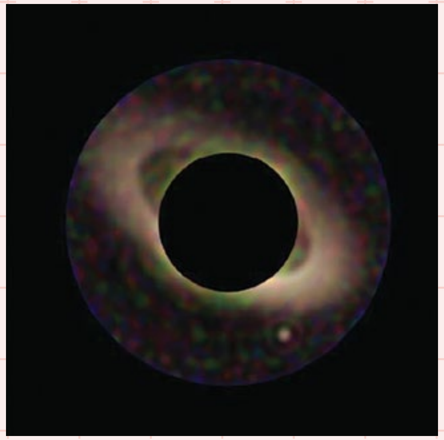
WFIRST is a mission concept that would directly image large exoplanets from reflected light. The telescope will also be capable of performing spectroscopy on exoplanet atmospheres, especially super-Earths, which are planets much like our own except larger. This spectroscopy would aid in determining whether these large terrestrial worlds might be capable of supporting life.

WFIRST would include the first high-contrast stellar coronagraph instrument ever flown and will utilize optical components created at JPL and Princeton University to directly image large exoplanets from reflected light. The telescope will perform spectroscopy on exoplanet atmospheres to help determine whether these worlds might be able to support life. WFIRST's complex optical train uses two types of coronagraphs, a hybrid Lyot coronagraph (HLC), designed and built at JPL, and a shaped pupil coronagraph (SPC) designed at Princeton University.

JPL's MDL is fabricating the masks for both. MDL is one of the few facilities in the world capable of creating these ultra-accurate optical components, which require grayscale lithography with nanometer-scale accuracy. The SPC uses a pupil-plane reflective mask that has ultra-dark regions of plasma-etched “black silicon” light-absorbing optics, which are fabricated and patterned using electron-beam lithography.

E-BEAM LITHOGRAPHY
The state-of-the-art JEOL JBX 9500FS Electron Beam Lithography System at MDL, which had its first official patterning write initiated in June 2017.

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



CORONAGRAPH INSTRUMENT IMAGE
Simulation of expected image with CGI on WFIRST of a planet (at about 5 o'clock) with non-zodiacal dust cloud.

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

Communication by Light

Deep Space Optical Communication: Detectors

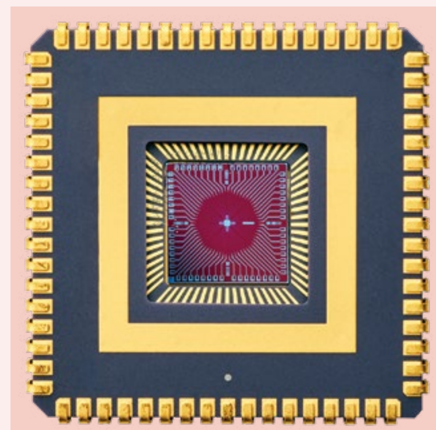
While design, nanofabrication, and testing of SNSPD devices are all performed at JPL, the technology development process for these devices has been highly interdisciplinary, with fruitful collaborations at the National Institute of Standards and Technology, the Massachusetts Institute of Technology, and Caltech.

SNSPDs are a key technology for optical communication. JPL SNSPD arrays were fielded on the ground in the Lunar Laser Communication Demonstration (LLCD) in 2013. They are also planned for the ground terminal of the Deep Space Optical Communication (DSOC) project, which is scheduled for launch in 2022 aboard the Psyche spacecraft. The DSOC project would be the first demonstration of laser communication from beyond lunar orbit and would extend the range of laser communication demonstrations by a factor of 1000 from what was achieved in the LLCD. To receive the faint signals from the laser transmitter on its cruise toward the asteroid belt, MDL has developed a unique 64-pixel SNSPD array sensor capable of time-tagging individual photon arrivals to sub-100-picosecond accuracy at count rates in excess of a billion counts per second.

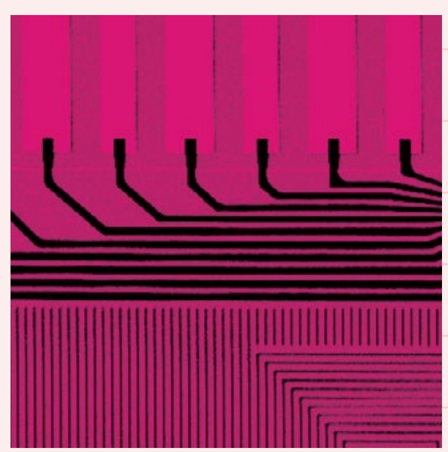
A cryogenic detector instrument based around this device will be fielded at the 200-inch telescope at Palomar Observatory in Southern California for use in the DSOC ground terminal. Delivery of the DSOC flight and ground terminals is expected in 2021. During the spacecraft's cruise phase, DSOC will demonstrate the viability of laser communication links at a variety of ranges up to 2.7 AU, beyond Mars' farthest range. With DSOC, the first demonstration of optical communication from deep space will place JPL in a strategic position to lead the Deep Space Network into the laser communication era.

Also being explored at JPL are large mid-infrared focal plane arrays of SNSPDs for exoplanet transit spectroscopy aboard future missions such as the Origins Space Telescope. In addition, ultraviolet SNSPDs are being integrated with ion trap chips for quantum computing applications.

The project manager for the DSOC mission at JPL is Bill Klipstein. Abi Biswas at JPL is the project technologist. The cognizant engineer for the ground detector instrument is Matt Shaw at MDL.



SNSPD ARRAY
A 64-pixel SNSPD array capable of counting over 1 billion photons per second with time resolution below 100 ps. The array is mounted in a chip carrier and can be efficiently coupled to a 5-meter telescope.

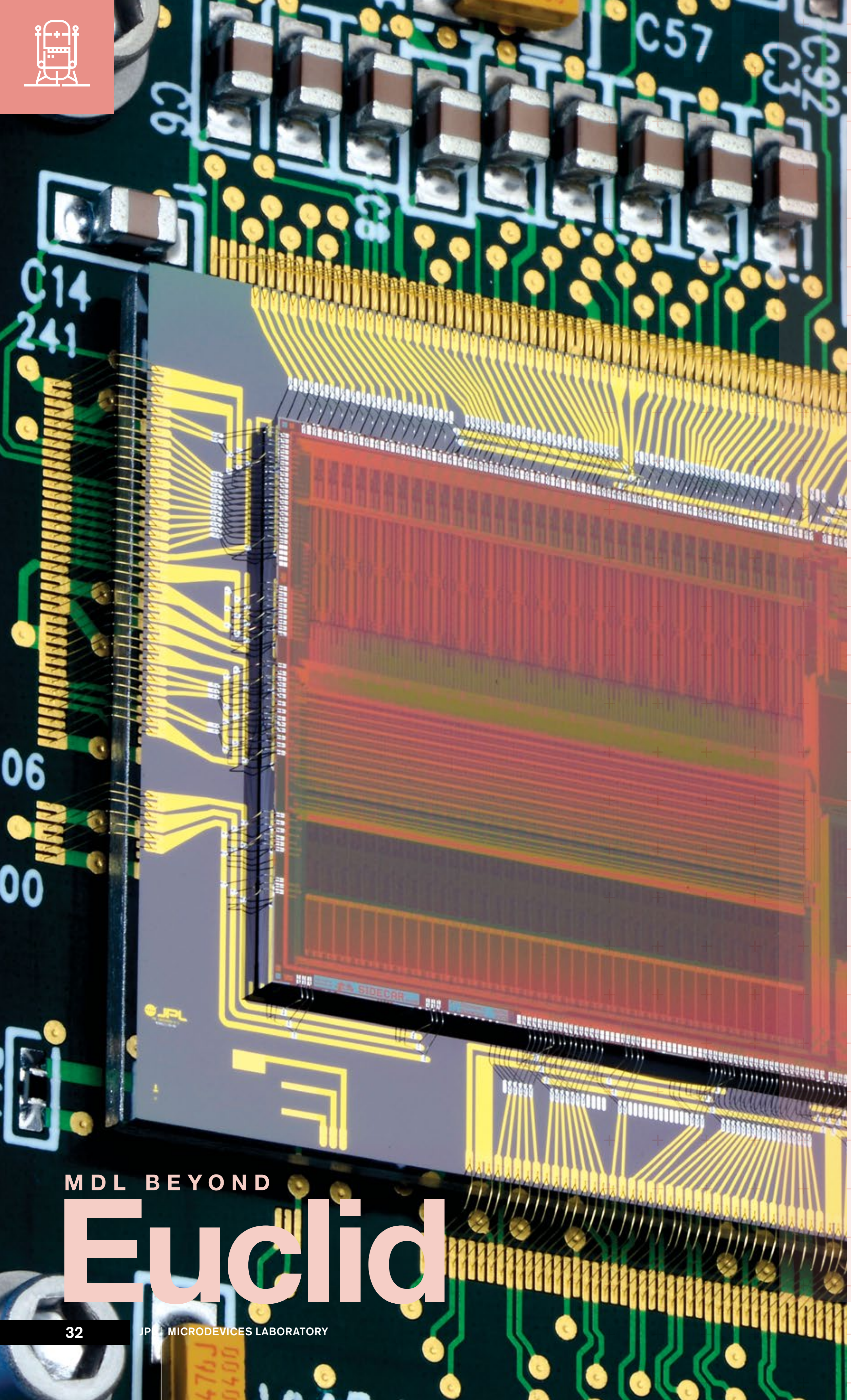


ARRAY WIRES
Scanning electron microscope (SEM) image of the SNSPD array.

Superconducting Nanowire Single Photon Detectors (SNSPDs) are the highest-performing detectors available from the ultraviolet to the mid-infrared range. Since 2005, MDL has been a world leader in the development of this unique technology and currently holds world records in SNSPD performance.

MDL BEYOND Psyche

PSYCHE.
An artist's concept of the Psyche spacecraft, which will conduct a direct exploration of an asteroid thought to be a stripped planetary core.



MDL BEYOND

Euclid

Euclid Mission

Scheduled to Launch in 2022

Euclid is a European Space Agency (ESA)–led mission to orbit a telescope at the Sun-Earth L2 Lagrangian point to conduct a comprehensive survey of galaxies over approximately one-third of the sky. This survey will be used to develop a map of the distribution of mass in the universe, which will then allow powerful tests of cosmological theories.

The focal plane of the Euclid telescope contains a visible light instrument and a near-infrared spectrophotometer (NISP). In 2019, NASA/JPL will complete delivery of 16 “sensor chip systems” composed of infrared detectors, cables, and cryogenic electronics to ESA and the NISP team in France. The detector arrays and application-specific integrated circuit (ASIC) chip used in the cryogenic electronics were provided by Teledyne Imaging Systems in Camarillo, California. The NASA team, including engineers at JPL and the Goddard Space Flight Center, have developed a package for the ASIC that works with high reliability at cryogenic temperatures.

The package is based on chip-on-board architectures used for JPL’s Spectral and Photometric Imaging Receiver (SPIRE), Goddard’s Thermal Infrared Sensor (TIRS), and Goddard’s Microshutter Arrays to launch on the James Webb Space Telescope.

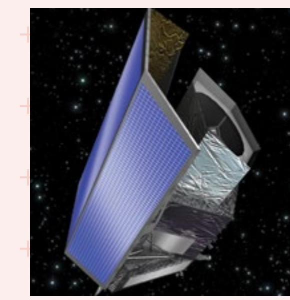
> POWERFUL TESTS OF COSMOLOGICAL THEORIES”

All of these components were operated successfully in space at deep cryogenic temperatures well below 130 K, the operating temperature required for the Euclid ASIC. MDL manufactured flight silicon fan-out boards for the new ASIC package. This silicon fan-out is necessary to interface the fine wire bond pitch on the ASIC with a wider wire bond pitch on the printed circuit boards.

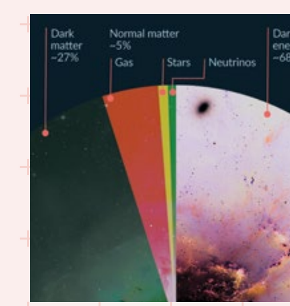
The silicon fan-out fabrication leverages an EX6 stepper photolithography system to produce all units quickly and with near-100-percent yield. JPL is also performing the epoxy attachment of the silicon components to the metal housing, of the fine wire bonding of the fan-out to the wiring board, and from the ASIC to the fan-out. These processes have been specifically developed by NASA/JPL to survive thermal cycling to cryogenic temperatures.

They are directly applicable to electronics that will be built for future missions to outer planets’ moons, such as Europa, Enceladus, and Titan, and for cutting-edge, industry-leading “Earthbound” technologies, such as superconducting quantum computing.

Giuseppe Racca is the Euclid project manager for the ESA, René Laureijs is the Euclid project scientist, and Jason Rhodes is the NASA representative on the Euclid science team. The technical lead for the cryogenic electronics packaging is Warren Holmes at MDL.



EUCLID SPACECRAFT This artist’s concept shows the Euclid spacecraft. A 1.2-m-diameter telescope with infrared detectors for science and data analysis.



EUCLID will address the question of why the expansion of the universe is accelerating and probe the nature of dark energy, which is responsible for this acceleration. Dark energy represents the majority of the energy content of the universe today and, along with dark matter, it dominates the content of the universe.

OPPOSITE PAGE Close up view of aluminum wirebonds from the ASIC to the silicon fan out and gold wire bond from the silicon fan-out to the printed wiring board.

SPARCS

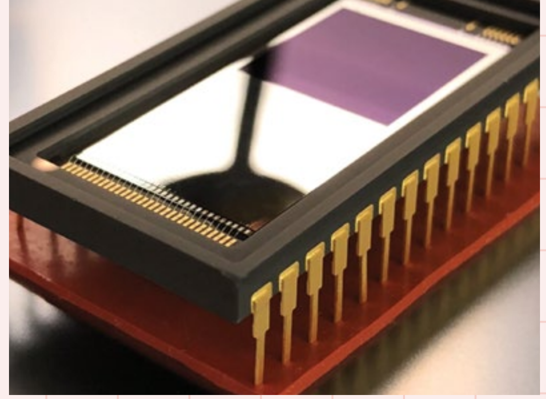
High-efficiency Detectors

The goal of SPARCS is to take a step back and examine the flares and other stellar activities of red dwarf stars, which are less than half the size of our sun and have 1 percent of its brightness.

There are about 40 billion red dwarf stars in the Milky Way galaxy, and the mission—with the help of unique ultraviolet sensors developed by MDL—will provide insight into habitable star systems and give researchers clues about how to interpret exoplanet data from bigger space telescopes.

In 2018, the SPARCS experiment was one of only two CubeSat missions selected for funding by the Astrophysics Research and Analysis program, which manages the Astrophysics CubeSats and suborbital missions for NASA. SPARCS would be the first mission to provide dedicated, long-duration UV observations of red dwarf stars. SPARCS achieves this in a six-unit CubeSat—the size of a cereal box—by using a small telescope and high-performance UV camera. Astrophysics missions typically depend on large-aperture telescopes and thus have been more challenging to fit the form factor of small CubeSats. With innovations in high-efficiency silicon UV detectors, where the need for high voltage and bulky detectors is eliminated, astrophysics UV CubeSat missions like SPARCS are becoming a reality. The data gathered by SPARCS would help scientists better understand exoplanet habitability potential by revealing their UV environment. These data are crucial to interpreting observations of planetary atmospheres in the context of their host star, whose ultraviolet activity may affect the nearby planets' atmospheric signatures and our assessment of their habitability.

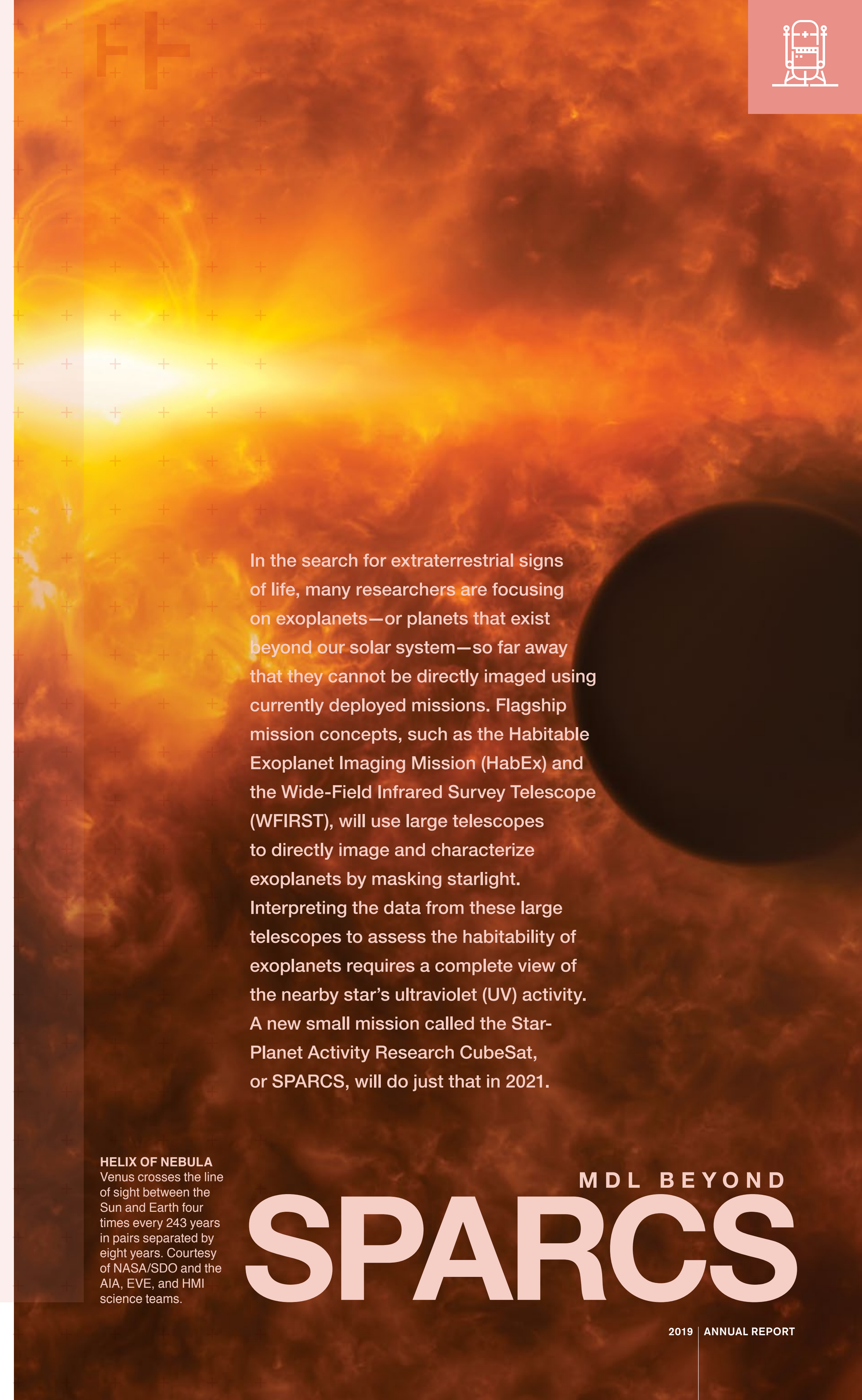
> INSIGHT INTO HABITABLE STAR SYSTEMS



DETECTORS
The SPARCam detectors are 2D doped CCDs that are individually optimized for the SPARCS FUV and NUV bands.

SPARCS is a collaborative effort between JPL and Arizona State University. JPL is responsible for delivery of the SPARCam, an ultraviolet camera with two channels in the far ultraviolet (FUV) and near ultraviolet (NUV). At the heart of the SPARCam are the detectors, each with a response tailored at MDL to optimize the SPARCS science return by maximizing the sensitivity to each spectral band while rejecting out-of-band light—a breakthrough for silicon detectors. Silicon detectors are used universally on NASA missions, creating images that are crucial for the entry, descent, and landing process, as well as providing images for necessary context in scientific measurements. Image-tube-based detectors have been used extensively in the ultraviolet spectral range in the past; however, they are bulky, have low sensitivity, and require high voltage. With advancements made at MDL, silicon detectors now have a UV response five to ten times higher than any flight instrument image-tube detectors. Through nanoengineering, researchers have made it possible to produce silicon arrays with unprecedented capabilities. They have achieved tailorable responses such that these silicon detectors have high sensitivity in the ultraviolet while rejecting background from visible and infrared sources. In collaboration with the industry, MDL is leveraging investments in silicon imaging technology to develop and deliver unique ultraviolet sensors based on the latest silicon detector designs.

The principal investigator for SPARCS is Professor Evgenya Shkolnik at Arizona State University's School of Earth and Space Exploration. The principal investigator for the SPARCam is Shouleh Nikzad at MDL, and April Jewell at MDL is the lead for the detector.



In the search for extraterrestrial signs of life, many researchers are focusing on exoplanets—or planets that exist beyond our solar system—so far away that they cannot be directly imaged using currently deployed missions. Flagship mission concepts, such as the Habitable Exoplanet Imaging Mission (HabEx) and the Wide-Field Infrared Survey Telescope (WFIRST), will use large telescopes to directly image and characterize exoplanets by masking starlight. Interpreting the data from these large telescopes to assess the habitability of exoplanets requires a complete view of the nearby star's ultraviolet (UV) activity. A new small mission called the Star-Planet Activity Research CubeSat, or SPARCS, will do just that in 2021.

HELIX OF NEBULA
Venus crosses the line of sight between the Sun and Earth four times every 243 years in pairs separated by eight years. Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

MDL BEYOND SPARCS

Future missions to the Moon will need to address fundamental science knowledge gaps about the abundance, sources and sinks of lunar volatiles and ascertain the potential of the lunar surface to provide resources for future human exploration.

FOR USE ON FUTURE LUNAR SURFACE MISSIONS"

MDL BEYOND

UCIS-Moon

To the Moon via Mars

An Ultra-compact Imaging Spectrometer for the Lunar Surface

An instrument developed originally for exploration of Mars is now being directed to the Moon under the DALI (Development and Advancement of Lunar Instruments) program.

The project will advance an ultra-compact shortwave infrared imaging spectrometer (UCIS) for use on future lunar surface missions, including expected commercial lander ventures. It is being developed so that it can be proposed in response to any future announcement of a landed lunar flight opportunity. It will maintain its low volume, mass and power requirements to be suitable for diverse landed platforms.

UCIS is currently capable of collecting spectra from 600 to 2600 nm. For this lunar application, the spectrometer detector will be upgraded to extend the spectral range to 3600 nm. The extension to 3600 nm is critical to detect, attribute, and map lunar water resources—specifically, the form, abundance, spatial distribution, and temporal variability of lunar OH species, molecular water, and water ice—as well as organics. In addition to volatiles, the extended wavelength range to 3600 nm will enable UCIS to detect organic material that may be present, delivered to the moon via impact of external, organic-rich solar system objects. UCIS will maintain its capability to map the mineralogical composition and geologic context of the lunar surface, unraveling its geological history at unprecedented spatial scales (meters to microns depending on optics).

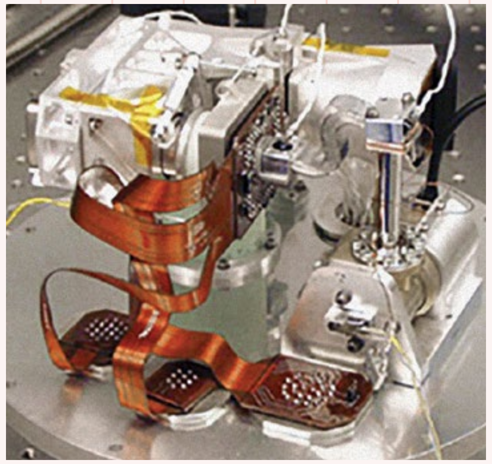
The development will also include new on-board analysis to enable return of high-value spectra while reducing the volume of transmitted data. This will be done by adapting existing algorithms based on (1) endmember detection and (2) fitting continuum-removed absorptions.

These strategies can be used to identify unanticipated materials and detect known high-value target signatures, respectively. Prioritized downlink of key spectra and derived maps will ensure fast, efficient landed operations. Onboard analysis will enable investigation lifetimes as short as one lunar day while still obtaining full maps of the landing site.

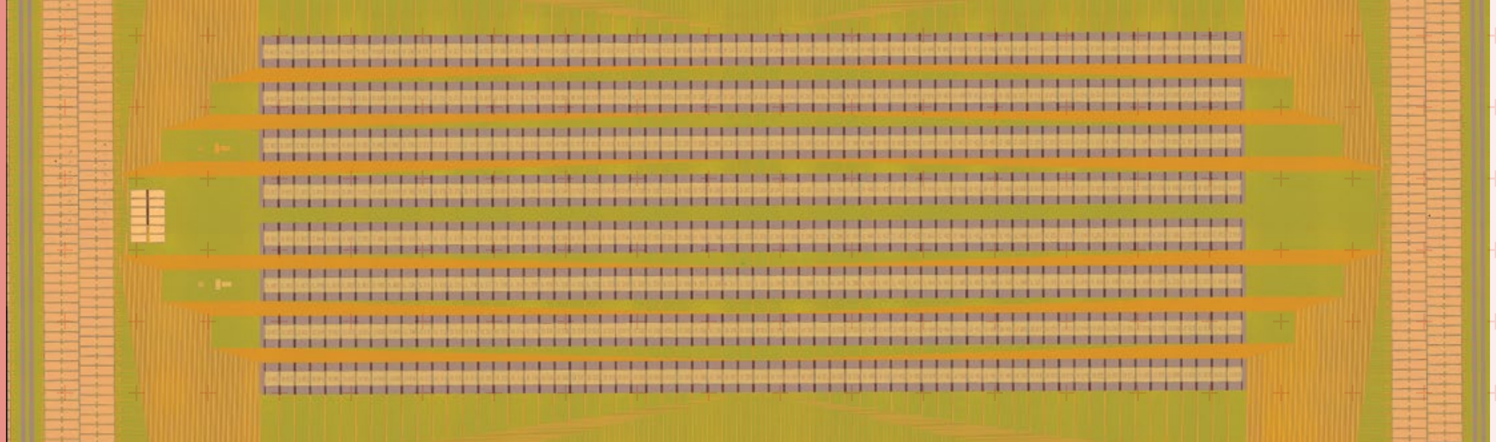
Finally, the UCIS instrument will be adapted to operate in the challenging thermal environment of the lunar surface. Temperatures on the surface of the moon can range from approximately 100 – 400 K, and reach even lower temperatures of ~30 K on permanently shadowed lunar ice deposits.

The advanced UCIS thermal design will allow operation in this wide temperature range while maintaining excellent signal-to-noise-ratio and sensitivity. A high-precision mode will be included to allow useful measurements from terrain scattered light in permanently shadowed regions.

The principal investigator is Abigail Fraeman.



ULTRA-COMPACT IMAGING SPECTROMETER
UCIS is a first-of-its-kind imaging spectrometer weighing less than 3 kg and consuming less than 3 W.



THERMOPILE ARRAY
At the heart of the FPM is a thermopile array, shown above. There are 8 spatial rows with 64 spectral channels spanning 5-50 μm. Around the perimeter of the array are 512 pairs of bond pads that wire bond to readout integrated circuits.

Arctic Heat

Why is the North Pole Warm?

In 2018, NASA selected the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) to perform first-of-their-kind infrared and far-infrared (FIR) measurements of Earth's atmosphere from space. One key question PREFIRE will attempt to answer is: Why is the Arctic warming faster than the rest of the planet? PREFIRE will fly two CubeSat satellites making radiometric measures of the atmosphere. CubeSats are lower-cost, lightweight, and very small compared to traditional satellites—each is about the size of a loaf of bread.

PREFIRE will use a JPL-designed instrument that uses critical technology from MDL, including a fully custom thermopile detector array. This thermopile array will help probe this little-studied portion of the radiant energy emitted by Earth for the first time, seeking clues about Arctic warming, sea ice loss, and ice-sheet melting. Finally, PREFIRE will explore how changes in thermal infrared emissions at the top of Earth's atmosphere are related to changes in cloud cover and surface conditions below. More than 60 percent of energy radiated from the cold, dry polar regions resides in FIR wavelengths. Energy in these bands is both dynamic and poorly characterized, yet it plays a critical role in defining the rapidly evolving polar climates.

The two PREFIRE CubeSats will make radiometric measures of the atmosphere between five to 50 micrometers, completely characterizing the variability in FIR emission on scales of hours to months.

This spectral data provides critical insight into surface emissivity, its variability, and the atmospheric greenhouse effect, allowing quantitative modeling of the surface/atmosphere feedback that is hypothesized to amplify the effects of climate change.

The dual spacecraft measurement capability specifically creates sub-diurnal sampling that can test the hypothesis that time-varying errors in current models of FIR surface emissivity cause biases in estimates of the energy exchange between the surface and the atmosphere of the Arctic. Elucidation and mitigation of these biases through PREFIRE measurements and analyses may reduce the large spreads observed in past projected rates of Arctic warming, sea-ice loss, ice sheet melt, and sea level rise.

Performing the required accurate and sensitive radiometric measurements across infrared and FIR wavelengths in a miniaturized satellite is challenging, but fortunately, PREFIRE will have the help of MDL's focal plane module (FPM). In particular, the FPM will use a thermopile detector array designed and fabricated at MDL with a pixel and format size customized for PREFIRE. The array operates uncooled, so minimal resources are needed to integrate the array into each CubeSat. Each pixel of the thermopile detector array has a broadband optical coating called "gold black" that provides near-unity optical efficiency across the entire spectrum that PREFIRE will measure. Finally, the FPM will utilize custom readout integrated circuits built by Black Forest Engineering that show no measurable low-frequency noise. Therefore, the entire FPM can observe the Earth over long integration times to enhance the signal-to noise ratio of the measurement.

The principal investigator for PREFIRE is Tristan L'Ecuyer, associate professor of atmospheric and oceanic sciences at the University of Wisconsin –Madison. The principal investigator for the thermopile detector is Matt Kenyon at MDL.

MDL BEYOND

PREFIRE

As our planet continues to warm, climate scientists need novel ways of exploring the processes that drive change and of measuring the markers that predict such alterations. These scientists recognize that the remote Arctic region of Earth is unique in that it helps regulate the planet's temperature like a thermostat by radiating back into space much of the excess energy from the Sun that is received in the tropics. However, more than half of these Arctic emissions occur at far-infrared wavelengths greater than 15 micrometers and have never been systematically measured from space before.

SEA ICE
2011 composite satellite image shows the expanse of Arctic sea ice and the Greenland Ice Sheet.

INSIGHT INTO THE SURFACE EMISSIVITY, ITS VARIABILITY, AND THE ATMOSPHERIC GREENHOUSE EFFECT"

MDL BEYOND

TIME

MDL detectors for the Tomographic Ionized Carbon Mapping Experiment.

Installation of TIME cryostat into 12-m ALMA prototype antenna at Kitt Peak National Observatory in Arizona.

Mapping the First Galaxies

TIME (the Tomographic Ionized Carbon Intensity Mapping Experiment) is the first instrument for a spectral imaging array to investigate the early history of the universe.

TIME (the Tomographic Ionized Carbon Intensity Mapping Experiment) is the first instrument of its kind, a spectral imaging array designed to map the emission of carbon monoxide and ionized carbon from distant galaxies. The main science motivation is investigation of the epoch of reionization, the period in the history of the universe when the first stars and galaxies formed from primordial hydrogen and helium. The planned survey will map CII as a tracer of ionized matter in this era, reconstructing the history of reionization by using the line to map ionized bubbles without resolving faint galaxies individually. The work is a collaborative effort between the Caltech Observational Cosmology group, JPL, Rochester Institute of Technology, the University of Arizona, and Academia Sinica Institute of Astronomy and Astrophysics in Taiwan. The TIME instrument is a novel mm-wavelength grating spectrometer that uses two banks of 16 parallel-plate waveguide spectrometers, each coupled to a single polarization of radiation.

The spectrometers are cooled in stages by a ^3He refrigerator to stabilize at 0.25 K. The spectrometer banks use curved diffraction gratings to disperse and focus collected light onto output arcs that are then absorbed by a series of closely packed detector arrays designed for a spectral range of 200-300 GHz and a resolving power of $\lambda/\Delta\lambda \sim 100$. The heart of each pixel array is a transition edge sensor (TES) bolometer coupled to a gold absorber on a suspended silicon nitride micro-mesh. These detector arrays were fabricated at MDL for TIME, which serves as a first-generation instrument to demonstrate observing methods to carry out these challenging measurements. Future designs developed at JPL will use spectrometers fabricated entirely from lithographed structures, resulting in highly compact spectroscopic arrays amenable to mass fabrication for developing larger and more-capable spectroscopic focal plane arrays.

During an engineering run at the 12-m ALMA Prototype Antenna on Kitt Peak in Arizona, TIME detected first astronomical light. These preliminary results are a first step forward towards completing the full instrument and the scientific observations to come.

The collaboration includes JPL members Prof. Jamie Bock (Caltech/JPL), Matt Bradford, Tzu-Ching Chang, Clifford Frez, Anthony Turner, Alexis Weber, Bruce Bumble, and Matt Kenyon. Work on TIME was supported by JPL and the Caltech President and Director's Research and Development Fund.

WHEN THE FIRST STARS & GALAXIES FORMED FROM PRIMORDIAL HYDROGEN & HELIUM ”

OWLS Project

Looking for Life on Ocean Worlds

The Ocean Worlds Life Surveyor (OWLS) is the first project funded under the JPL NEXT Program.

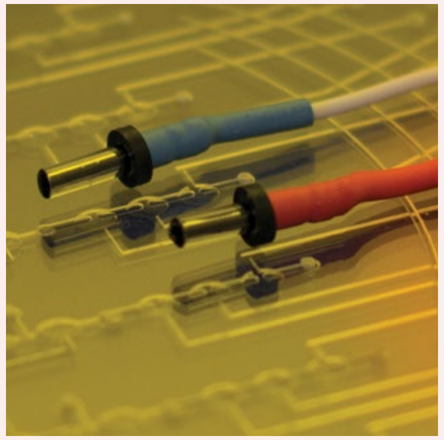
Initiated in 2018 after over a decade of pre-project NASA and JPL funding in planetary instrument development, the goal of the OWLS project is to build and validate the first field instrument prototype capable of autonomously performing molecular and cellular analyses essential for life detection. Hence, OWLS paves the way for future spaceflight astrobiology missions to ocean worlds of the outer solar system, such as Europa and Enceladus. By the time of project completion in 2021, OWLS will develop and test a field prototype in the Borup Fjord Pass in the Canadian High Arctic, a location that serves as a compelling analogous environment for ocean world missions.

The OWLS instrument has two major subsystems to perform molecular and cellular analyses. To perform molecular analyses, OWLS uses capillary electrophoresis-laser-induced fluorescence (CE-LIF) detection to look for amino acids and carboxylic acids, capillary electrophoresis capacitively coupled contactless conductivity (CE-C4D) to detect charged species, and capillary electrophoresis-electrospray ionization coupled to mass spectrometry (CESI-MS) for broad-based detection and characterization of collections of organic molecules.

To perform cellular analyses, OWLS uses the Digital Holographic Microscope (DHM) to detect the number, composition and motion of particles and the Volume Fluorescence Imager (VFI) to identify biomolecules associated with the objects identified in the DHM. Using all five detection methods will be key in acquiring multiple lines of evidence for the presence of life on ocean worlds, should we encounter it during a future mission of exploration.

Over the past year, three new OWLS prototype systems have been developed and tested in the laboratory. Each system breadboard has been verified to function as desired, and field testing will be performed at a coastal ocean site in Summer 2019 to validate end-to-end system function outside the laboratory, prior to initiation of the next stage of instrument development, where integrated brassboard systems will be developed and validated.

ELECTROSPRAY IONIZATION MASS SPECTROMETRY. Above (and only just visible) is the tip of an electrophoresis capillary especially designed by JPL partners at the SCIEX corporation for spraying liquid samples into a mass spectrometer.



UMS SENSORS
Batch fabricated UMS sensors.

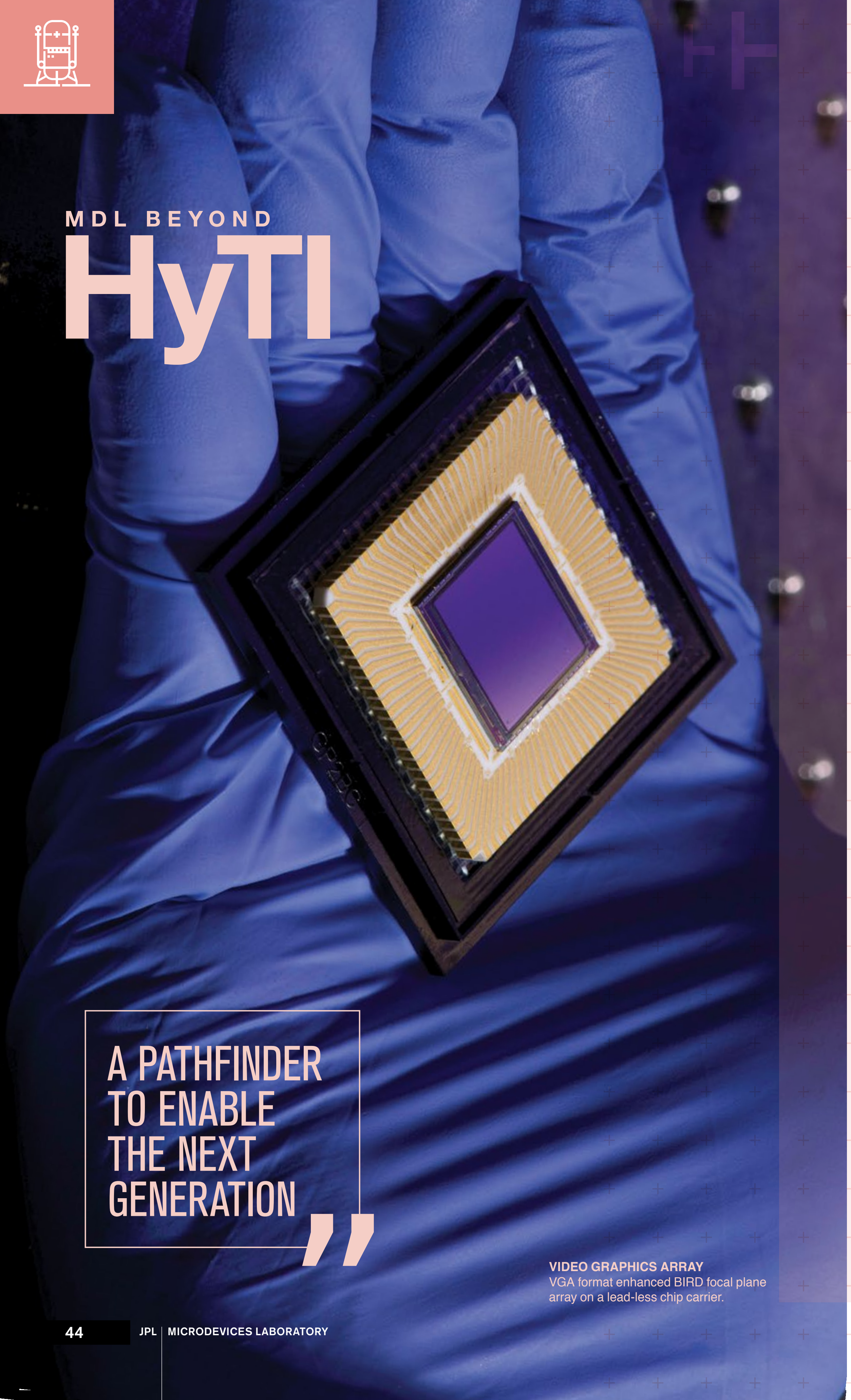
ELECTROCHEMICAL SENSORS
Electrochemical sensors developed at MDL for measurements of ions present in liquid samples (shown in relation to microfluidic valves and pumps used for fluidic routing).

OWLS PAVES THE WAY FOR FUTURE SPACEFLIGHT ASTROBIOLOGY MISSIONS"

Members of the OWLS project will build the Field Prototype Instrument to take to Borup Bjord Pass in the Canadian High Arctic, a location that serves as an analog environment for ocean worlds such as Enceladus and Europa.

MDL BEYOND

OWLS



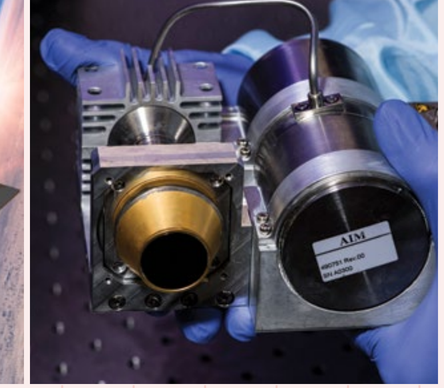
MDL BEYOND

HyTI

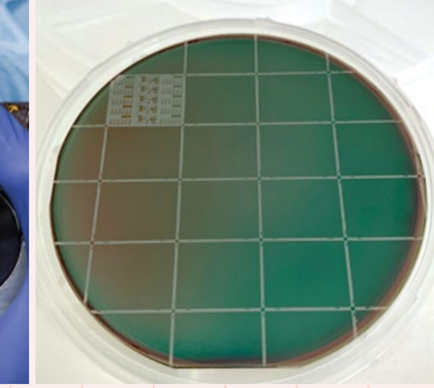
A PATHFINDER TO ENABLE THE NEXT GENERATION

VIDEO GRAPHICS ARRAY
VGA format enhanced BIRD focal plane array on a lead-less chip carrier.

HYTI
Illustration depicting the HyTI CubeSat in low Earth orbit.



DEWAR COOLER
This image shows a prototype integrated dewar cooler assembly.



DETECTOR ARRAY
HyTI detector array wafer.

Taking Earth's Temperature from a CubeSat

Hyperspectral Thermal Imager (HyTI) is a test of the technology that will become the next generation of low Earth orbit imaging spectrometers.

Monitoring global hydrological cycles and water resources and developing a detailed understanding of the movement, distribution, and availability of water and its variability over time and space are critical needs for NASA's Decadal Strategy for Earth Observation from Space. An associated need is the measurement of land surface dynamics by monitoring the continuous variability of land surface temperature (LST). While low earth orbital (LEO) hyperspectral thermal infrared (TIR) observations will enable detailed measurements of both hydrological and LST variability, their focus will be on enabling agricultural remote sensing. Thus, the NASA Earth Science Technology Office (ESTO) In-space Verification of Earth Science Technologies (InVEST) Program has funded the design, build, assembly, test, and flight of a 6U CubeSat LEO demonstration of the HyTI as a pathfinder to enable the next generation of high spatial, spectral, and temporal resolution TIR imagery acquisition from LEO. HyTI is being designed to investigate global food and water security issues by mapping both irrigated and rain-fed cropland areas to determine crop water use (actual evapotranspiration) of major world crops and thereby establishing the crop water productivity ("crop per drop") of major world crops.

JPL will supply the long-wavelength Barrier Infrared Detector (BIRD) focal plane array (FPA), integrated dewar cooler assembly, and the FPA driver electronics as the payload for HyTI. The Hawaii Space Flight Laboratory (principal investigator Dr. Robert Wright) is responsible for system engineering, spacecraft assembly, and flight operation of HyTI. The heart of the HyTI hyperspectral imager is a novel long-wavelength two-dimensional BIRD FPA designed and developed at MDL.

The BIRD is a breakthrough infrared detector technology based on band-gap engineered multi-layer III-V semiconductor structures that exploit quantum effects to provide continuous adjustability in infrared cutoff wavelengths while simultaneously delivering high signal-to-noise ratio and providing the advantages offered by the robustness of III-V semiconductors. This technology has evolved over many years. Development of the enhanced HOTBIRD, with improved architecture customized for HyTI, required constant exploration and experimentation in device architecture design, material growth, device fabrication and measurement. The well-maintained, state-of-the-art facilities in MDL are essential to the success of JPL's infrared focal plane development effort for NASA and other government application programs. The launch of the HyTI SmallSat in 2021 under the NASA CubeSat Launch Initiative program will be the first opportunity to demonstrate the BIRD technology in space. The BIRD development effort at JPL is funded by the NASA ESTO programs, defense and intelligence programs, and JPL internal investment programs.

SECTION 3

MDL BEYOND

MDL KEEPING AHEAD

The JPL vision for the future and the **JPL Strategic Technology Directions** document call out specific projects and innovative processes but specifically mention MDL technologies. MDL has always pursued a way of working that shows a cycle of continuous innovation, process and product development, and implementation in missions. To achieve this state, any given snapshot of MDL activities must reveal work at all developmental stages, from the pursuit of an innovative idea to the customization of a product for a specific mission. However, for this approach to be successful, the right people are essential. These are the people who will help fulfill the focus of the Strategic Technology Directions document.

A CYCLE OF CONTINUOUS INNOVATION, PROCESS AND PRODUCT DEVELOPMENT, AND IMPLEMENTATION"

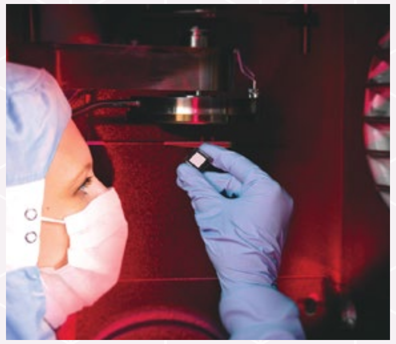
MDL BEYOND

Creating the lab of the future

The JPL Microdevices Laboratory (MDL) was established with the goal of providing capabilities for development of components, sensors, and instruments for the JPL/NASA space program. MDL products have to support JPL's strategic mission and business base, providing novel and unique technologies that are the basis of competitive proposals and successful missions/projects. In order to maintain and excel at MDL's current leadership role, it is essential to identify and engage high quality researchers and programs that are targeted toward future important scientific and technical goals of NASA and JPL utilizing the existing and expanding capabilities at MDL.

The postdoctoral program at MDL has been a great channel to bring the next generation of technologists to MDL. Examples abound. The following are just two examples.

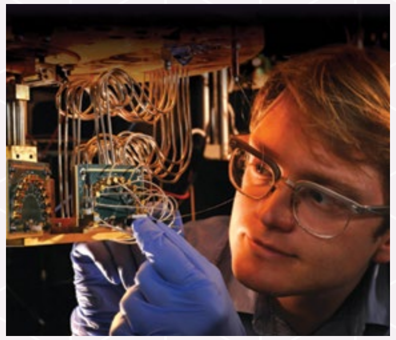
CECILE JUNG



I first came to know of JPL during my 2005 Master internship at Bell Laboratories in New Jersey, where I met scientists and engineers who had previously worked at JPL. A few months later, I went back to France and started my Ph.D with the Paris Observatory. My Ph.D advisor, Dr. Alain Maestrini, had done a postdoc at JPL and he rapidly introduced me to his former colleagues who in turn became my colleagues. I received a NASA Postdoctoral Program (NPP) fellowship in 2009. I had met my postdoc advisor, Dr. Imran Mehdi at various conferences during my Ph.D, and he was the former advisor of my Ph.D advisor. I started my postdoc at JPL in early 2010, as part of the Submillimeter Wave Advanced Technology (SWAT) group. I spent two years as a postdoc in the SWAT group working on the development of silicon etching techniques, and I received the JPL 2010 Outstanding Postdoctoral Research Award for my work in the field of Technology, Instrumentation and Engineering. During my second year, my group supervisor, Dr Peter Siegel, offered me a full-time position that I started in early 2012. I stayed in the SWAT group for another 5 years, working at MDL on silicon microfabrication techniques for the miniaturization of THz instruments and propulsion systems. In 2017, I was selected to join the newly formed Electron Beam Technologies group to infuse new ideas for the next generation of microfabricated devices, but I maintained my projects and involvement with the THz community and the SWAT group.

In 2018, I was awarded the prestigious Lew Allen Award for Technical Excellence for my work in the development of novel electromagnetic, mechanical and propulsion systems. I am a senior process engineer at MDL and a member of the E-beam Technologies group, with Dr Daniel Wilson. I am still working on silicon micromachining techniques to miniaturize instruments, and my scope of work now also involves RF MEMS, THz antennas, GaAs Schottky diode detectors and, more recently mass spectrometers. My projects are mostly research oriented, to advance the state of the art (SOA) and propose new solutions for future JPL and NASA missions. At JPL, we aim to develop new capabilities, but we also keep a close connection with industry, and I am the Contracting Officer for several Small Business Innovation Research (SBIR) projects. Last but not least, I am mentoring postdocs and Ph.D students, training them on cleanroom processes and silicon etching techniques, and encouraging them to develop strong skills and experiences that will advance their careers.

MATT SHAW

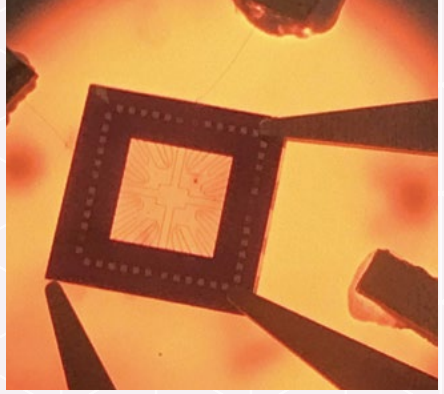


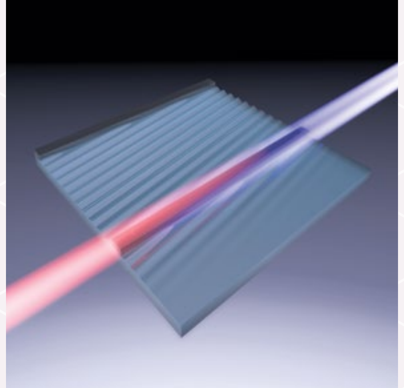
I grew up in the farthest reaches of the Earth, in Fairbanks, Alaska. When I was 11 years old, my father took me to a special live screening of Voyager's flyby with Neptune at the University of Alaska, which had set up a direct video conference line with Building 230 at JPL. It amazed me that the engineers at JPL could make contact with a world so cold and distant and to be able to see images of that world for the first time.

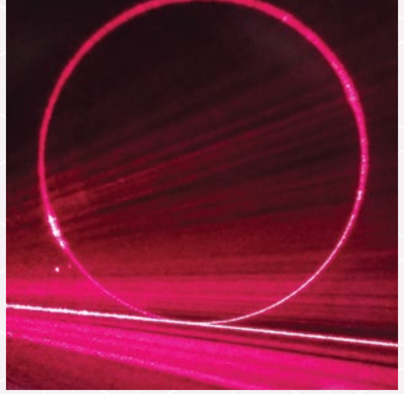
When I began as a graduate student at the University of Southern California, one of the first things I did was to ask all of the professors if they knew of anyone doing research at JPL. I was put in contact with Pierre Echternach at JPL, who agreed to serve as my research advisor. Pierre taught me an incredible amount about low temperature physics, nanofabrication, superconducting devices, and electronic instrumentation. In the MDL cleanroom, I was able to learn from experts with decades of experience in superconducting device fabrication, including Rick Leduc, Bruce Bumble, Jeff Stern, and many others, who generously shared their time and expertise with me. The depth of experience available within MDL provided a learning environment that far surpassed what could have been possible in a university cleanroom, where graduate students typically learn from each other.

After finishing my Ph.D. research at JPL in 2009, I began working as a postdoc in the group of Keith Schwab at Caltech. During this time, I continued to come back to MDL to perform nanofabrication, where Rick Leduc and others helped me to develop as a researcher. In 2011, Jeff Stern's research in superconducting nanowire single photon detectors (SNSPDs) had advanced to the point where he was able to hire an additional staff member to assist him with device testing in the laboratory, and I was able to begin as a Microdevices Engineer in the Superconducting Devices and Materials Group.

My research interests are in the development of SNSPD technology and in the demonstration of free-space laser communication from deep space. The SNSPD team at JPL, which consists of myself, Emma Wollman, Andrew Beyer, Boris Korzh, Ryan Briggs, Jason Allmaras, Eddy Ramirez, and Andrew Mueller, is working on the support of laser communication ground terminals at JPL and on research and development tasks to improve the size, speed, time resolution, and wavelength response of SNSPDs and to infuse them into a variety of science experiments. I am the Cognizant Engineer for the ground detector assembly in the Deep Space Optical Communication project, which is the first-ever demonstration of laser communication from beyond lunar orbit, and I am the principal investigator for a variety of detector R&D projects.







MAX JONES

Max received his Ph.D. from Caltech, where he worked on nanoscale field emission transistors. These transistors are built with the same top-down fabrication techniques as silicon solid-state transistors but remove the crystalline conduction channel and gate oxide to allow electrons to ballistically travel through a nanoscale vacuum gap. This unique conduction mechanism enables these transistors to operate in extreme temperature and radiation environments where traditional semiconductor devices fail.

These environments are often encountered on space or exoplanetary missions, and Max's current research involves demonstrating circuits composed of these field emission transistors across a more than 500-degree temperature range. He is also interested in building photomultiplier tubes (PMTs) with microscale dimensions that would allow them to be pixilated and would relax the vacuum packaging requirement while retaining room temperature single photon detection. Building PMTs with microscale dimensions will also improve the responsivity and timing resolution of the device. This ultra-sensitive, high-time-resolution room-temperature detector array would improve time-sensitive measurements, including LiDAR.

> WE ARE NOW LOOKING FOR NEW TALENT & SEEKING TO HIRE OUTSTANDING POST-DOCTORAL RESEARCHERS "

ERIC KITTLAUS

Eric received his Ph.D. in applied physics from Yale University, where he worked in the group of Prof. Peter Rakich. At Yale, Eric developed optomechanical silicon waveguides that permit strong light-sound couplings through a process called stimulated Brillouin scattering. These devices enabled efficient silicon-based amplifiers and lasers, as well as nonreciprocal optical devices and narrowband microwave filters.

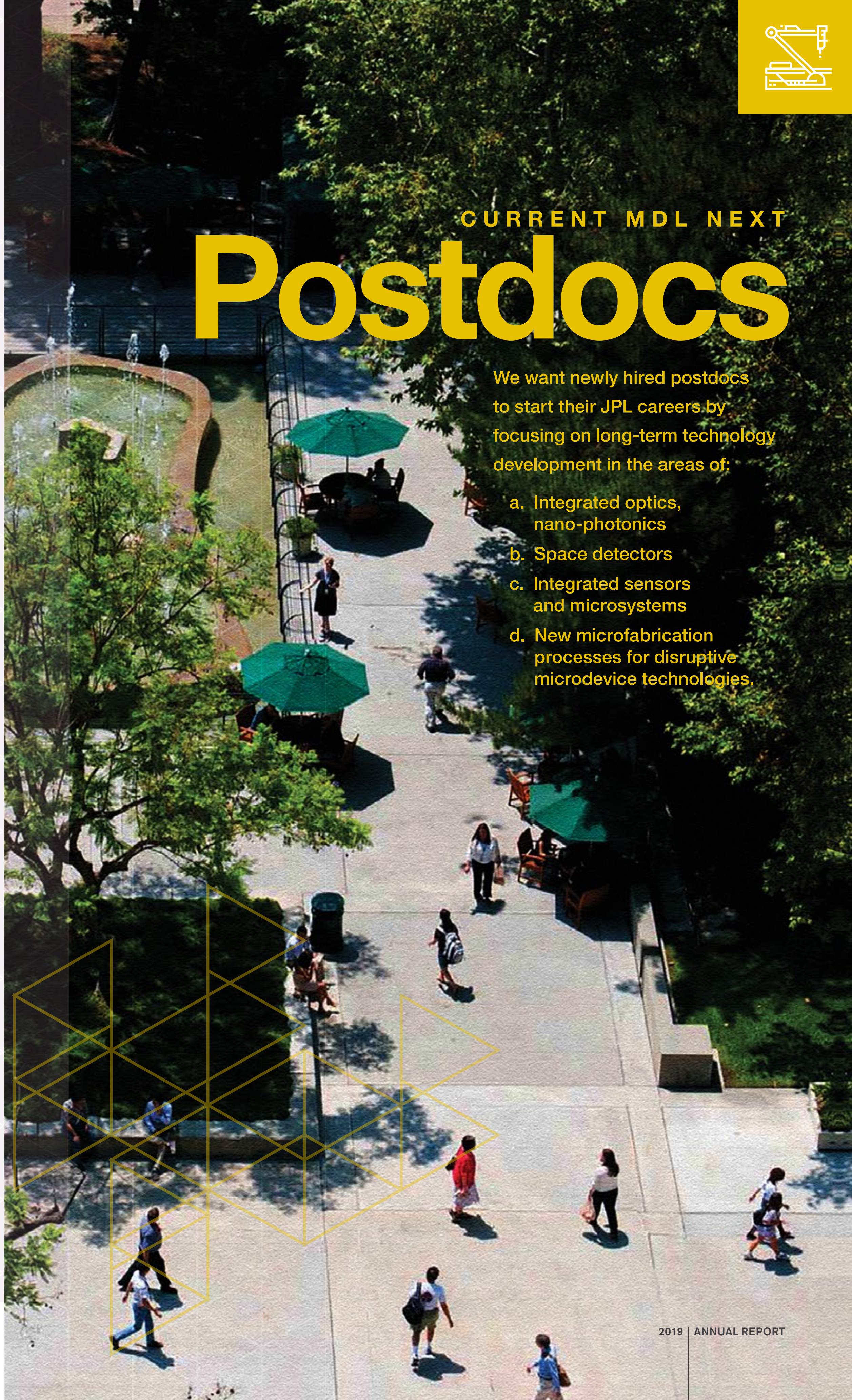
Eric's current research interests focus on the development of integrated platforms that simultaneously couple optical and microwave photons with acoustic phonons. Such systems provide fertile ground to explore new types of opto-acoustic interactions and permit flexible optical and microwave signal processing operations.

This technology will be utilized for applications ranging from optical sensing to future spaceborne radar systems, harnessing novel microscale photonic-phononic devices that possess superb sensitivity and reconfigurability.

PETER WEIGEL

Peter was first introduced to research in optics while at Lehigh University, where he graduated in 2013 with a B.S. in electrical engineering. Peter went on to study at the University of California San Diego, where he obtained his M.S. in 2014 and his Ph.D. in 2018, both in electrical engineering. During his graduate studies, Peter researched hybrid waveguide platforms and their applications, including passive, nonlinear, and electro-optic hybrid waveguide technologies. He focused in particular on developing beyond-100-GHz integrated near-infrared electro-optic modulators and plans to bring that technology expertise to JPL.

At MDL, Peter is developing in-house fabrication processes for ultra-low-loss waveguides and multi-layer waveguide platforms, an important step towards bringing reliable and customizable integrated photonics technology to JPL. His research interests focus on low-loss three-dimensional waveguide technologies, where heterogeneous stacks of materials can be used to build waveguides capable of passive and active operations not possible with single-material waveguides. These three-dimensional technologies and low-loss integrated waveguides may be useful for planetary exploration and analysis at UV, visible, and MIR wavelengths in particular, where traditional waveguides – designed for telecomm applications – are insufficient and where free-space optical solutions are heavy, large, and expensive.



CURRENT MDL NEXT

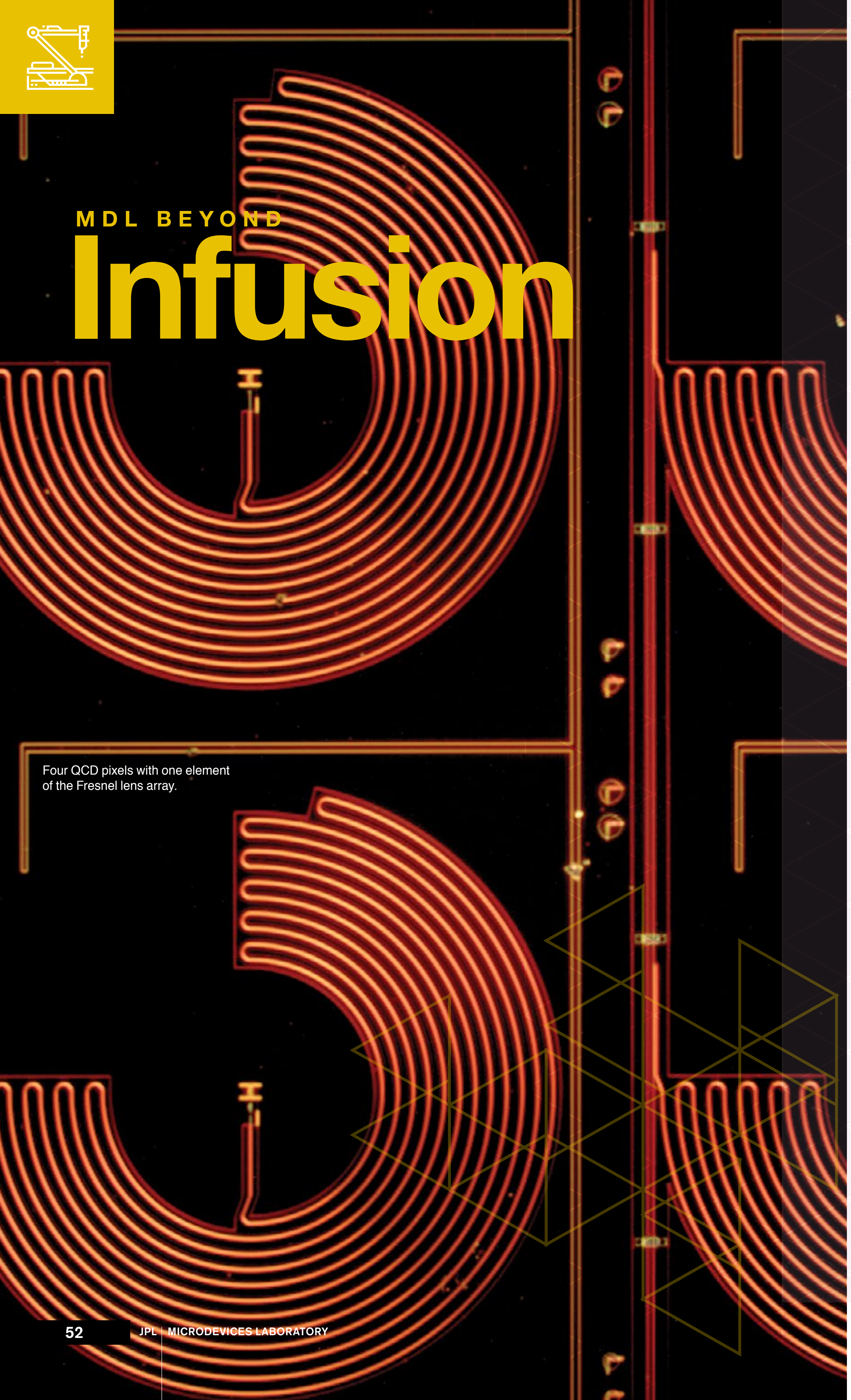
Postdocs

We want newly hired postdocs to start their JPL careers by focusing on long-term technology development in the areas of:

a. Integrated optics, nano-photonics
b. Space detectors
c. Integrated sensors and microsystems
d. New microfabrication processes for disruptive microdevice technologies.

MDL BEYOND

Infusion



Four QCD pixels with one element of the Fresnel lens array.

MDL Makes a Difference

In the long term, the impact of MDL is evaluated by its ability to continuously incorporate novel, or even disruptive technologies in space. New and viable ideas must be identified and incorporated into the current state of the art. As many advances could come from non-space sectors, such sectors must be actively researched for potential ideas.

This should mobilize both traditional national labs and universities to look for space technologies of the future, and to demonstrate technologies that are potentially disruptive, and not only incremental. Such highly innovative technologies should lead to radical improvements in performance and will enable emerging missions. Drastic improvements in miniaturization, efficiency, versatility and functionality are expected.

> …CONTINUOUS INCORPORATION OF NOVEL, OR EVEN DISRUPTIVE TECHNOLOGIES IN SPACE"

A number of challenges in space technologies have parallels to terrestrial challenges, for example in the fields of aeronautics, energy, environment, information and communications technologies, natural resource exploration, sensors, robotics, advanced materials and production methods, security and health.

What are disruptive observable technologies for space?

Are they mature enough to be carried out at MDL?

Are they synergistic with MDL core competencies?

Who are the pioneers and how we can team up with them?

As an example, we have identified integrated photonics and nano-photonics as areas for long-term technology development.

What is the rationale behind this choice?

JUSTIFICATION

Integrated photonics technology has matured enough to be considered for space.

Integrated photonics can provide reduced cost, size, weight, and power as compared to fiber or bulk optics.

SPACE BOUND APPLICATION

- Metrology
- Free-space optical communication and quantum communication (quantum key distribution)
- Spectroscopy
- LiDAR and microwave photonics

WHY AT MDL

- JPL is already using or plans to use integrated photonics components in their instruments
- Compatible with technical competency of MDL staff
- Compatible with microdevice fabrication tools at MDL
- Foundries for fabrication (AIM Photonics, etc.)

MDL NEXT

Develop fabrication processes at MDL

- Rapid prototyping of passive circuits
- Heterogeneous and hybrid integration
- New materials systems for low-temperature, different wavelength ranges, nonlinear optics, etc.
- Leverage MDL's grayscale E-beam capabilities

Provide testing capabilities

- Optical and electrical characterization

Provide an interface to outside foundries

- Design support
- Modelling, simulation, and layout

Keeping MDL at the Cutting Edge

Clearly, to be and to continue to be the partner of choice of scientists within and outside JPL, MDL must be at or beyond the state of the art in fabrication techniques and devices. How is this to be achieved?

The MDL approach is to make sure it is aware of current and emerging approaches in all sectors and then make selective capital equipment investments and the successive steps of planning and implementation.

Microfabrication equipment requires continuous upkeep and investment for three main reasons. First, the useful life of semiconductor fabrication equipment is typically 10 years or less due to normal wear and tear. While it is possible to “keep the lights on” through repair work and incremental continuous improvement, ultimately, some equipment needs to be retired and renewed just to maintain existing capabilities.

Second, over the last 25+ years, semiconductor processing technology has been and continues to be a rapidly evolving area. The vast majority of these technological innovations require novel equipment designs in order to practice them effectively. Therefore, it is not possible to make a minor upgrade to an existing piece of equipment in order to achieve state-of-the-art performance. To ensure that MDL continues its leadership in producing world-class scientific instruments and instrument components, MDL must also invest in new kinds of equipment to enable these state-of-the-art innovations.

Third, MDL has a dual role in developing new technologies and infusing them into flight missions. In certain circumstances, the equipment used to prove a proof of concept is not configured to be able to produce the number and quality of units necessary for flight applications. In those cases, existing capability must be scaled appropriately for flight opportunities now and in the future.

Preparing MDL for the Future

To appropriately forecast upkeep and investment needs, MDL maintains and annually updates an equipment acquisition plan aimed at ensuring that the laboratory will be able to fulfill its missions in upcoming years.

We have concluded that a level of investment of approximately $2.5 M/year is necessary to ensure that the equipment complement of MDL does not constrain the research that takes place or could take place at the facility. The JPL Executive Council has guaranteed MDL this level of funding for the next several years.

MDL has benefited significantly from JPL institutional support to sustain its central processing infrastructure and capital investments and to maintain its competitive edge, and it is important to have a plan to ensure those funds are invested wisely.

We continue to hire a number of outstanding post-doctoral researchers to focus on long-term technology development, most recently in the area of photonics, which is expected to make an impact on future spacecraft engineering by replacing or enhancing conventional electrical approaches in the fields of digital and rf telecom payloads, sensors, micro LiDARs and spectrometers by reducing the size, weight, power, or performance of the systems they replace.

Microwave photonics is being developed to offer new functionality and performance to RF payloads. At the core of these payloads are photonics to generate stable local oscillators, perform optical down conversion, and manipulate the optical microwave signals by routing, beamforming or filtering them in the optical domain. The main components include lasers, optical amplifiers, wavelength division multiplexing components, optical modulators, optical switches, and photonic integrated circuits for optical beam forming, switching and filtering.

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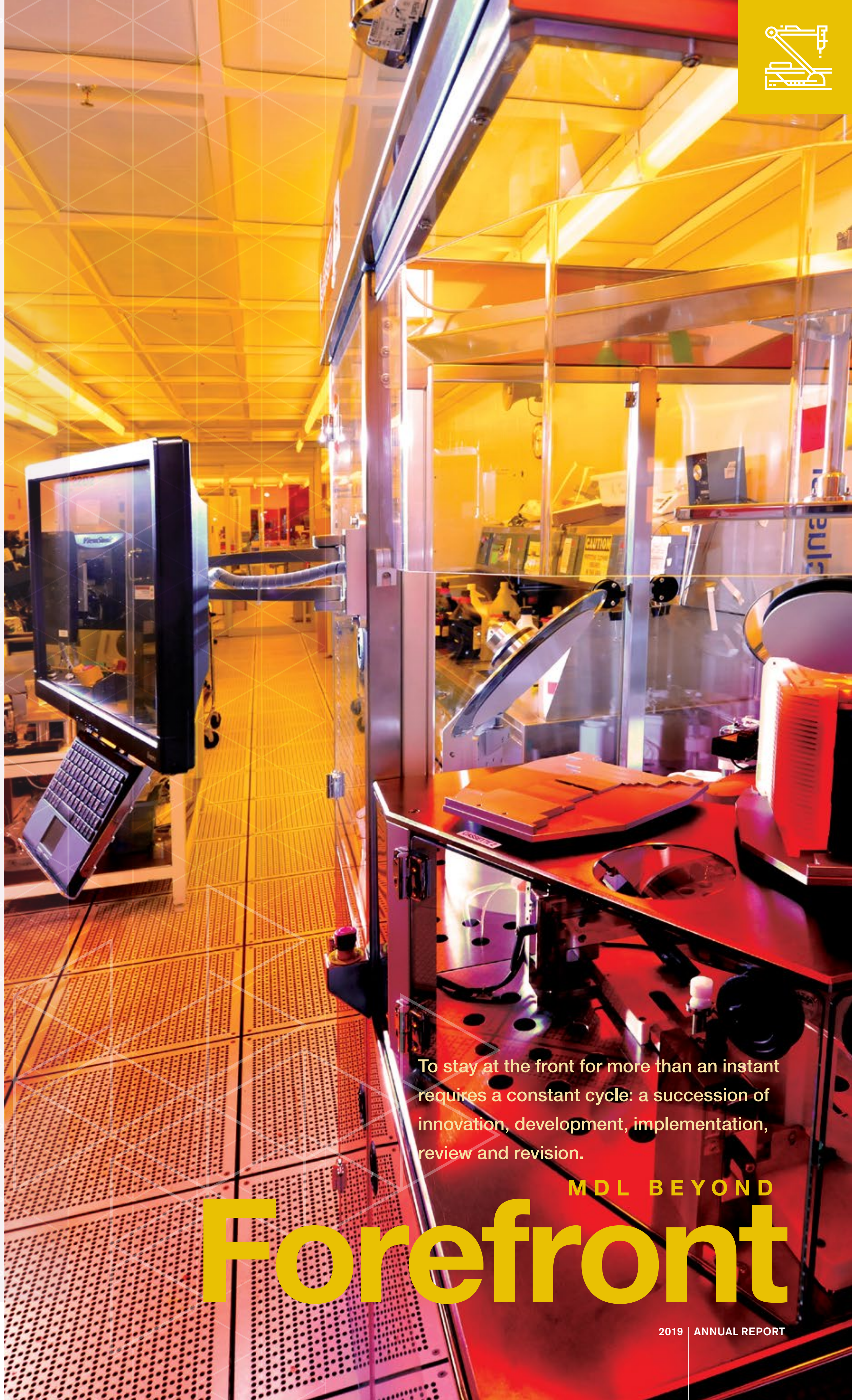

To stay at the front for more than an instant requires a constant cycle: a succession of innovation, development, implementation, review and revision.

MDL BEYOND

Forefront

MDL BEYOND

Enabling MDL

Sustained investments in and renewal of facilities and equipment are necessary to enable research, development, and deliveries from MDL for current and future JPL / NASA missions.

LEFT
MDL researcher viewing a sample in the new Hitachi Regulus 8230 UHR Cold Field Emission Scanning Electron Microscope.

RIGHT
The new Oxford PlasmaPro 100 Cobra Cryo Etcher for Black Silicon configured with additional Atomic Layer Etching and Deep Silicon Bosch Etching capabilities.

Infrastructure and Capabilities

Recent Key Strategic MDL Investments

MDL's infrastructure capability investments are strategically chosen to allow MDL to flexibly and nimbly meet future challenges and are aligned with the NASA and JPL strategic plans drawn from the National Academy of Sciences Decadal surveys. These investment choices cover a five year future period and are formalized as the **MDL Equipment Investment Plan**, which is updated regularly.

1) **Load-locked Oxford Plasma Pro 100 Cryo/ALE / Bosch Etcher System–** provides state-of-the-art cryogenic etching capability to make world-record light-trapping Black Silicon. This material applied to Offner and Dyson imaging spectrometers eliminates internal reflections and improves their performance. It is also used to fabricate occulting spots for coronagraphs, giving improved direct imaging of exoplanets. In addition, the new Atomic layer etching (ALE) capability can be applied in additive and subtractive manufacturing for 3D nanostructures, a strategic vision area for future structures allowing electromagnetic field manipulations.

2) **Maskless Heidelberg MLA150 Laser Lithography System–**necessary for the higher yields needed for the larger arrays being developed for astrophysics instrumentation and optical communications.

Additional strategic MDL equipment investments:

3) **Hitachi Regulus 8230 UHR Cold Field Emission Scanning Electron Microscope (SEM)–** provides improved characterization capabilities. t images with reduced charging and can dimension structures, identify material composition, and characterize defects and contamination on a microscale.

4) **Veeco Gen20 III-V (Sb) Molecular Beam Epitaxy (MBE)–** required to meet the delivery demand and unique cutting-edge requirements unavailable commercially for Mid IR and Far IR detectors. It is needed for numerous currently funded, proposed and future NASA deliverables. This is a multiyear acquisition with delivery and installation in 2020.

5) **Modernized Surfscan 6210 Wafer Particle Monitor–** to check and improve cleanliness levels in the MDL cleanrooms necessary for the higher yields needed as MDL moves to larger array processing with smaller, nanometer-scale structures.

6) **Oxy-Nitride Furnace Growth Tube–** addition to an existing TYSTAR system providing a missing processing capability essential for strategic integrated opto-electronic developments.

7) **Custom ALD / PVD–** system incorporating an in-situ combination of Atomic Layer Deposition (ALD) and Physical Vapor Deposition (PVD) for improved MgF_2 UV mirror coatings.

Other sustained infrastructure renewal investments improve and modernize performance and prolong the life of existing equipment and facilities in MDL. The strategy is to renew and replace computers, operating systems, software, hardware components, and subsystems such as pumps and power supplies as needed. Upgraded subsystems are also added to maximize available investment dollars, but they still retain and modernize functionality of both equipment and facilities. In 2018, seven major subsystem upgrades were made on equipment.

Plans to meet MDL infrastructure facility needs for the 2025-2035 timeframe:

Current MDL facility capabilities are footprint constrained and aging. MDL strategic visions require the processing of larger wafers with arrays with smaller feature sizes, as well as the addition of new capabilities and replacement of old ones, often with larger footprints. Examples of such enhancements in the near term include: Improving the quality of MDL's ultra high purity (UHP) water plant; Reducing sources of particles in MDL's cleanrooms; Converting some existing areas into cleanroom processing areas; Changing facilities to minimize downtimes, such as an electrical bypass for servicing MDL electrical switch banks; and Improving environmental monitoring and building controls to give better temperature, humidity, exhaust balancing, and electrostatic discharge controls while also addressing improved energy utilization. MDL continues to eliminate capabilities that are no longer needed.

In the long term, the JPL/NASA Construction of Facilities (CoF) request process has been initiated to construct an MDL NExT (New Exploration Technologies) building with enhanced capabilities in the 2035 timeframe.

FIU aims to develop strategies that will improve successful completion of science, technology, engineering and mathematics (STEM) degrees.

Reaching Out to Many

Research and Education Activities

An immediate first impression of all visitors to JPL is the immense variety of people. Diversity and inclusivity are intrinsic to the NASA and JPL cultures, so it is not surprising that MDL not only espouses this stance but also proactively engages and encourages the next generation of diverse potential recruits.

SIAMAK FOROUHAR
MOHAMMAD MOJARRADI
MARTY HERMAN

Since part of the mission of the NASA Office of Education is to advance high-quality STEM education across the United States, MDL has partnered with Dr. Daniela Radu of Florida International University (FIU, a Hispanic-serving Institution) with a proposal to the NASA Minority University Research and Education Program (MUREP).

The research. The center will develop the research infrastructure needed to address some of the most important challenges of space exploration through strong partnerships with NASA Centers. We will explore novel two-dimensional functional materials to be incorporated into sensors, wearable electronics, integrated optics / photonics, and energy generation devices for space applications. Characterization of devices and materials in extreme space environments (temperature and radiation) will be an overarching theme. The projects will engage many students for training at FIU and NASA Centers.

Educational Relevance. The STEM Transformation Institute at FIU will lead the educational program. Students will also be able to participate in summer internships at NASA Centers, yearlong undergraduate internships on campus, and curricular interventions, including courses on the behavior of materials and electronics in space and topical Senior Project Design capstones. Resources at NASA Centers will be leveraged through undergraduate and graduate student internships on testing materials and devices in space conditions.

On July 10, 2019, NASA announced that this proposal was one of only eight – of 56 received – that will receive funding.

INSPIRING THE WORLD THROUGH OUR STORIES ”

A visitor admires a rover wheel at the 2018 “Explore JPL.”

MDL BEYOND

Outreach

FIRST robotics team in Guilford, CT.

VALERIE SCOTT

Dr. Valerie Scott is an experimental and analytical chemist with an extensive background in chemistry, catalysis, analysis and characterization, and developing techniques and instrumentation relevant to multiple engineering problems. Her academic work included research on carbon–fluorine bond activation and reaction mechanisms of carbon–hydrogen bond activation and catalytic conversion of methanol into fuels.

JPL and MDL have always been committed to letting the world know what we are doing. Although it is part of the NASA ethos, it is also valuable in exciting and enthusing future generations of employees and collaborators.

Inspiring Others

After Being Inspired Herself

In the fall of 2018, I gave an outreach talk to the **FIRST robotics team** from my hometown (Guilford, CT). While this group was non-existent when I was in high school and was in its infancy when my little sister was a student, it has evolved into a serious local team, largely under my father's guidance. Because of his continuous involvement, I was invited to give a talk so that these aspiring engineers could hear what it is like to work at JPL and ask questions. While the audience was mostly high school students, there were a number of parents, siblings, and previous FIRST team members present, totaling about 60 people. I gave a seminar on technology development and how it relates to the science that we learn, specifically focusing on Mars-related science. I spoke a bit about Spirit and Opportunity, Curiosity, Insight, and about the upcoming Mars 2020 missions. Because I spoke just days before Insight's landing, I tried to highlight some of the upcoming science, along with relevant technologies. The students asked lots of great questions, including very specific planetary science topics, what my day-to-day work activities are like, and advice about college.

Also, I was invited as a guest lecturer to talk at **CalState Channel Islands** about my nontraditional path as a chemist, how I ended up at JPL, and a high-level discussion of the types of projects I work on. I spoke to a group of about 40 undergraduate chemistry majors. I talked very broadly about several technology projects I have worked on over the years and attempted to tie in how my chemistry background fed into these technologies. With chemistry education, students are frequently exposed to common analytical techniques but often take the instrumentation complexity for granted and do not know the challenges of implementing these techniques on a space exploration mission. I tried to connect their chemistry classes' content to technology development, and eventually how these developments might one day address specific science questions.
—Valerie Scott

Using lessons from NASA/JPL educational activities as a jumping off point to engage students in citizen science using real NASA data.

ALEX SOIBEL

Dr. Soibel worked on the development of quantum cascade lasers for the tunable laser spectrometer of the Mars Science Laboratory and is currently engaged in the development of infrared imagers for various space- and Earth-based applications. He has co-authored more than 50 refereed articles and four book chapters.

High-level Teaching

Low-level School Students

As part of an education and outreach effort, I am teaching a physics class for 6th through 8th graders at a **STEM program** for children organized by the Caltech Postdoctoral Association and sponsored by the Caltech International Office. The program was organized a year and a half ago, and it is developing and testing new models of educating children from kindergarten to 12th grade (5 to 18 years old). The program is free, voluntary and open to members of the JPL and Caltech communities. Students are divided into small groups and receive a well-rounded education in STEM. Each teacher develops their own curriculum based on the goals of the class and may also provide alternative ways of interacting with the information on a conceptual level. In addition, the program is pioneering a new approach in which high school and middle school students, many of whom are long-time students of the UCLA math circle (math.ucla.edu/~radko/circles/), teach classes to the elementary school students, thus contributing to the much less formal atmosphere of the program.

I have been teaching the physics class for the last five months. There are 12 students in my class, ages 12-14, and about half of them are girls. We meet every Monday for an hour of lectures, and the students are also given homework and reading assignments. The program level is close to that of an AP physics class; its curriculum is based on Khan Academy physics classes and the book "Physics for scientists and engineers" by R. A. Serway. The goal of the class is to provide insight into physics and to prepare students to take an AP physics class.

My involvement in community activities also includes serving as a judge at the **LA Science Fair** and the **California Science Fair**.
—Alex Soibel

MDL has a considerable range of internal expertise in many technical and scientific areas. Nevertheless, there are many examples in which partnering with an external institution produces mutual benefits that are greater than the sum of their parts. In one such example, MDL expertise in the space qualification of unique semiconductor lasers has been combined with the challenging measurement requirements of atmospheric components.

WE LOOK FORWARD TO CONTINUING AND STRENGTHENING OUR COLLABORATION, PURSUING NEW AVENUES"

MDL BEYOND

Collaboration

A Highly Successful MDL Collaboration with Harvard

Since 2010, Harvard University professor Jim Anderson and MDL's Siamak Forouhar have been jointly pursuing the development of high-power pulsed and continuous wave laser systems for demanding spectroscopic applications associated with Earth and planetary sciences.

This collaboration has the potential to revolutionize three key areas of research:

1. **The application of Harvard's integrated cavity output spectroscopy** technique to the *in situ* measurement of isotopes, radicals, and reactive intermediates in the troposphere and stratosphere;
2. **The advancement of Harvard's two-photon laser-induced** fluorescence *in situ* measurement of the OH and HO_2 radicals in the troposphere and stratosphere; and
3. **The advancement of the LiDAR detection of methane**, which operates in concert with Harvard's high-spatial-resolution airborne observations of methane and carbon dioxide isotopic fluxes from melt zones in the Arctic basin.

This partnership has already resulted in two success stories. Firstly, in 2017, Harvard flew a laser developed at MDL as part of a NASA Advanced Component Technologies Program grant on a NASA high-altitude research balloon. This was part of the NASA Undergraduate Student Instrument Project. The distributed-feedback interband cascade laser was packaged with a thermoelectric cooler and integrated lens to produce a collimated beam in the 3.3 μm region. The flight profile included four hours of float time, during which the balloon utilized controlled helium releases to step down from 96,000 to 50,000 feet in altitude. The laser and instrument performed well in this demanding thermal environment and successfully acquired measurements throughout the flight's operational phase A.

Secondly, the Harvard instrument team was a major part of the Dynamics and Chemistry of the Summer Stratosphere proposal that was selected for the Earth Ventures Suborbital-3 program. This selection means that multiple MDL infrared lasers will soon be making sustained airborne measurements from the NASA ER-2 high-altitude aircraft.

OPPOSITE PAGE. NASA's ER-2 high-altitude Earth science aircraft is used for environmental science, atmospheric sampling, and satellite data verification missions. Harvard Professor Anderson has a history of using this aircraft for stratospheric measurements in his research.

Professor Anderson has expressed his team's appreciation for the extremely productive collaboration between JPL and Harvard. Furthermore, he has acknowledged that the quality of MDL lasers and the dedication of Dr. Forouhar and his team have been essential ingredients in this scientific success. In Professor Anderson's words, "We look forward to continuing and strengthening our collaboration, pursuing new avenues such as active remote sensing." Following this successful collaboration, Professor Anderson recently visited JPL and met with JPL's chief technologist, Director for Earth Science and Technology directorate, Manager of the Earth Science formulation office, and researchers. From these discussions, it became apparent that JPL and Harvard should form a partnership in advancing science and technology and formulating airborne missions through future EV-S opportunities. An initial array of research interests and opportunities to advance this collaboration was identified as follows:

LiDAR instrument development. Pursue a small form factor LiDAR development for sensing greenhouse gases.

EV-S concept development. Explore enabling capabilities for airborne applications. The revolutionary Odysseus long-duration, solar-powered, stratospheric aircraft is a candidate vehicle for such an opportunity in that it provides, for the first time, the capability to quantitatively establish the mechanisms responsible for large-scale stratospheric circulation. Over the next few years, a joint team will pursue various research efforts to develop an array of critically imperative stratospheric science objectives for the EV-S program.

Technology infusion. There have been many synergistic technology exchanges with Harvard. JPL has identified a few areas to continue these exchanges in anticipation for future funding opportunities.

Here are few of the candidate technologies

- Meta materials with a focus on lenses, mirrors, etc.
- Integrated photonics
- Data science/machine learning
- Leveraging existing designs to miniaturize laser/detector electronics
- Formation flying and autonomy

Stories of collaboration continue on pg. 64

... stories of collaboration continued from pg. 63

MDL-Caltech Partnership to Understand Star Formation

Creating a team between a scientist with a drive to understand a fundamental problem and the provider of a possible solution can be mutually valuable and satisfying.

MDL has expertise in developing ultraviolet detectors with unprecedented performance.

Shouleh Nikzad and her team at MDL have been collaborating with Caltech Professor Chris Martin to improve UV science returns via technology that will allow world-class astronomy with the highest possible payoff in throughput and telescope aperture size. Nikzad's focus is on ultraviolet detectors, while Professor Martin studies the history of star formation in galaxies and the physical conditions that govern this history. He is particularly interested in how the baryonic gas that begins as the inter-galactic medium ultimately finds its way into galaxies and stars.

Martin and Nikzad, along with Professor Schiminovich of Columbia University, co-led a Keck Institute for Space Studies Workshop to define key science questions and identify and develop enabling technologies for UV instrumentation and missions. They have also jointly proposed and won multiple NASA proposals for the development of novel detectors; they develop, demonstrate, and infuse key enabling technologies. They have shared recent success in the first flight of the FIREBall balloon mission (September 2018). Nikzad and Martin's complementary expertise has led to fruitful developments, most notably the successful development of ultraviolet photon counting detectors on FIREBall.

Nikzad and Martin will likely team up with JPL for the next NASA MIDEX missions call.

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MDL-Arizona State University Infusion Collaboration on Habitability of Exoplanets

The NASA tag, "**Are we alone?**" encompasses a large range of activities looking for the possibility of Life outside the Earth.

A good start in seeking habitable planets is to find those of a suitable size at the right distance from an appropriately sized star. But what if the radiation from that star were not conducive to the origin and continuation of Life?

Professor Evgenya Shkolnik studies the effect of the UV environment of stars in research on the habitability of planets in the habitable zone.

MDL has expertise in high-performance ultraviolet detectors and in instrument miniaturization.

Launching a normal, orbiting UV observatory would be a very expensive mission. However, reducing the satellite to a much smaller format makes such a mission feasible. The Star-Planet Activity Research CubeSat (SPARCS) is a small space telescope about the size and shape of a family-size Cheerios box. The mission which SPARCS will monitor the flares and sunspot activity of M-type stars, also called red dwarfs, in the far- and near-ultraviolet. The purpose is to assess how habitable the space environment is for planets orbiting these stars.

Professor Evgenya Shkolnik and Shouleh Nikzad, MDL, have begun a collaboration in pursuit of this fundamental topic through the CubeSat, SPARCS, which should be ready for launch in late 2021. The mission's results will eventually lead to addressing the question "**Are we alone?**"

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MDL BEYOND

Visiting Committee

COLLABORATION

DR. THOMAS L. KOCH
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Dean of College of Optical Sciences and Professor of Optical Sciences
University Of Arizona

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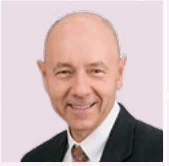
University of Alberta

DR. WILLIAM HUNT
Professor of Electrical Engineering,
Georgia Institute of Technology

MR. GEORGE KOMAR
Retired Program Director,
NASA Earth Science Technology Office (ESTO)



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California Institute of Technology

DR. JONAS ZMUIDZINAS
Former JPL Chief Technologist, former Director of JPL's Microdevices Laboratory, and Merle Kingsley Professor of Physics,
California Institute of Technology

Meeting every two years to review the ongoing work at MDL and make valuable suggestions for future directions, they have acknowledged that MDL is a key national asset with unique state-of-the-art capabilities and staff well-focused on space applications of micro- and nanotechnologies.

The Visiting Committee, consisting of a broad spectrum of highly talented and accomplished individuals, has recognized the leadership, vision, and innovation of MDL. The committee's inputs have been of tremendous value in the pursuit of the highest quality research and development programs targeted toward the key scientific and technical goals of interest to NASA and our other sponsors.

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Appendix

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2. Bell, D., S. Nikzad, E. Rocco, J. Marini, and S. Shahedipour- Sandvik. "Progress inCesium- Free III-Nitride Photocathodes Based on Control of Polarization Charge" In Semiconductor Surfaces and Nano-structures, American Physical Society, Los Angeles, Mar. 2018.

3. Bell, Douglas, E. Rocco, F. Shahedipour-Sandvik, S. Nikzad, "Cesium-Free III-Nitride Photocathodes Based on Control of Polarization Charge," American Vacuum Society 65th International Symposium, Long Beach, CA (2018).

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BOOK CONTRIBUTIONS

1. Chattopadhyay, G., M. Alonso-DelPino N. Chahat, D. González-Ovejero, C. Lee., and T. Reck (2018) Terahertz Antennas and Feeds. In: Boriskin A., Sauleau R. (Eds) Aperture Antennas for Millimeter and Sub-Millimeter Wave Applications. Signals and Communication Technology. Springer, 2018.

NEW TECHNOLOGY REPORTS

1. Cochrane, C.J., "Self-Calibrating Solid-State Based Magnetometer for Vectorized Field Sensing Via Zero-Field Spin Dependent Recombination," NTR NPO 49854.

2. Kehl, F., P. Willis, "General Purpose Plunger Based Fluidic Extractor for In Situ Planetary Exploration," NTR # 50725.

PATENTS

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2. K.A. Moffat, D. Nikolić, V.M. Farrugia, J. H. Wosnick, A. Kovalenko, A.Kobryn, S. Gusarov, Carboxylic Acid or Acid Salt Functionalized Polyester Polymers, U.S. Patent 9,982,088, Issued May 29, 2018.

3. B. Karasik, J. Kawamura, M. Sherwin, M. Huang, C. Yoo, L. Pfeiffer, K. West, "Tunable Antenna-Coupled Intersubband Transition (TACIT) Heterodyne Detector for High- Resolution Far-IR Spectroscopy of Gaseous Bodies in Solar System." US patent pending.

AWARDS & RECOGNITION BY EXTERNAL ORGANIZATIONS

1. Pierre Echternach
The JPL Edward Stone Award for Outstanding Research Publication 2018; Single photon detection of 1.5 THz radiation with the quantum capacitance detector.

2. Sarath Gunapala
SPIE George W. Goddard Award in Recognition of Exceptional Achievement in Optical or Photonic Instrumentation for Aerospace, Atmospheric Science, or Astronomy.

3. Sarath Gunapala
MSS (Military Sensing Symposia) Levinstein Award for "outstanding technical and management contributions in the development of infrared focal plane arrays for the military sensing community and national defense under the Vital Infrared Sensor Technology Acceleration (VISTA) program."

4. Sarath Gunapala
SPIE George W. Goddard Award, presented annually in recognition of exceptional achievement in optical or photonic instrumentation for aerospace, atmospheric science, or astronomy.

5. John Hennessy
IEEE Senior Member status

6. Michael Hoenk
SPIE Senior Member status

7. April Jewell
The SPIE Defense and Commercial Sensing 2019 Rising Researcher Award

8. Cecile Jung-Kubiak
The JPL Lew Allen Award for Excellence 2018; For demonstrated excellence in the development of innovative silicon micromachining techniques that have enabled novel electromagnetic, mechanical, and propulsion devices.

9. Steven Schowalter
AVS Vacuum Technology Division Early Career Award Winner 2018

10. Jose Siles
The JPL Lew Allen Award for Excellence 2018; For the development of high-power ultra-compact room-temperature multi-pixel terahertz sources and receivers for balloon-borne and space instruments.

11. D. Ting, A. Soibel, A. Khoshakhlagh, S. Rafol, C. Hill, A. Fisher, B. Pepper, S. Keo, E. Luong, J. Mumolo, J. Liu, And S. Gunapala
MSS (Military Sensing Symposia) Herschel Award for NASA's Jet Propulsion Laboratory HOT-BIRD (High Operating Temperature Barrier Infrared Detectors) Technology.

12. David Ting, Alexander Soibel, Arezou Khoshakhlagh, Sir Rafol, Cory Hill, Anita Fisher, Brian Pepper, Sam Keo, Edward Luong, Jason Mumolo, John Liu, and Sarath Gunapala
MSS Herschel Award for NASA's Jet Propulsion Laboratory HOT-BIRD (High Operating Temperature Barrier Infrared Detectors) Technology.

13. David Ting
IEEE Photonics Society Distinguished Lecturer Award is to honor excellent speakers who have made technical, industrial or entrepreneurial contributions to the field of photonics and to enhance the technical programs of the IEEE Photonics Society Chapters.

MDL EQUIPMENT COMPLEMENT

Material Deposition

- Thermal Evaporators (5)
- Electron-Beam Evaporators (7)
- Angstrom Engineering Indium-Metal Evaporator
- AJA Load Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- PlasmaTherm 790 Plasma Enhanced Chemical Vapor Deposition (PECVD) for Dielectrics with Cortex Software Upgrade
- 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 (150-mm/6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 2 Tubes for
  - Low-Stress Silicon Nitride
  - Atmospheric Wet/Dry Oxidation
- Carbon Nanotube (CNT) Growth Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  - Veeco GEN200 (200-mm/8-inch) Si MBE for UV CCD Delta Doping (Silicon)
  - Veeco Epi GEN III MBE (Antimonide Materials)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (3)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (3)

Lithographic Patterning

- Electron-Beam (E-beam) Lithography: JEOL JBX9500FS e-beam lithography system with a 3.6-nm spot size, switchable 100,000 & 48,000-volt acceleration voltages, ability to handle wafers up to 9 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 10 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7-μm res.)
- Canon FPA3000 i4 i-Line Stepper (0.35-μm res.)
- Canon FPA3000 EX3 Stepper with EX4 Optics (0.25-μm res.)
- Canon FPA3000 EX6 DUV Stepper (0.15-μm res.)
- 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 with SW upgrade
- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 Etcher
- Oxford PlasmaPro 100 Cobra Load-Locked Cryo Etching / Atomic Layer Etching / Bosch Etching System, primarily for Black Silicon.

Chlorine-based Plasma Etching Systems

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

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
- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Jelight UVO-Cleaners (2)
- Novascan UV8 Ultraviolet Light Ozone Cleaner
- 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 with upgrade
- SurfX Atomflo 500 Argon Atmospheric Plasma Surface Activation System for wafer bonding

Appendix, cont.

- New Wave Research EzLaze 3 Laser Cutting System
- Indonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher
- Laurell Technologies Dilute Dynamic Cleaning System (DDS), Model EDC 650 – a Dilute HF/Ozonated DI Water Spin Cleaning System with MKS Instruments Liquizon Ozonated Water Generator.
- Osiris Fixxo M200 TT Wafer Mounting Tool

Packaging

- SET FC-300 Flip Chip Bump Bonder
- Karl Suss Wafer Bonder
- Electronic Visions AB1 Wafer Bonder
- EVG 520Is Semi-Automatic Wafer Bonding System
- 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 and Alphastep 500)
- Frontier Semiconductor FSM 128-NT (200-mm/8-inch) Film Stress and Wafer Bow Mapping System
- LEI 1510 Contactless Sheet Resistance Tool
- FISBA μPhase 2 HR Compact Optical Interferometer
- Horiba UVSEL 2 (190–2100 nm) Ellipsometer
- Filmetrics F20-UV (190-1100 nm) Thin Film Spectrometer Measurement System
- Filmetrics F40-UVX (190-1700 nm) Thin Film Spectrometer Measurement System with Microscope
- Bruker Dimension 5000 Atomic Force Microscope (AFM)
- Park Systems Inc. NX20 Atgomic Force Microscope (AFM)
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- JEOL JSM-6700 Field Emission SEM with EDX
- Hitachi Regulus 8230 UHR Cold Field Emission SEM with Aztec Energy Dispersive X-ray Microanalysis System and Critical Dimension Measurement capabilities.
- Nanospec 2000 Optical Profilometer
- Nikon and Zeiss Inspection Microscopes with Image Capture (3)
- Keyence VHX-5000 Digital Microscope including low power lens
- McBain BT-IR Z-Scope IR Microscope Workstation
- Olympus LEXT 3D Confocal Microscope
- Mitaka NH-5Ns 3D Profiler
- Electrical Probe Stations (4) with Parameter Analyzers (2)
- RPM2035 Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectrometers (3) including Bruker Optics Vertex 80 FTIR
- 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 Profile
- Thermo Scientific LCQ Fleet CE / MS (Capillary Electrophoresis / Mass

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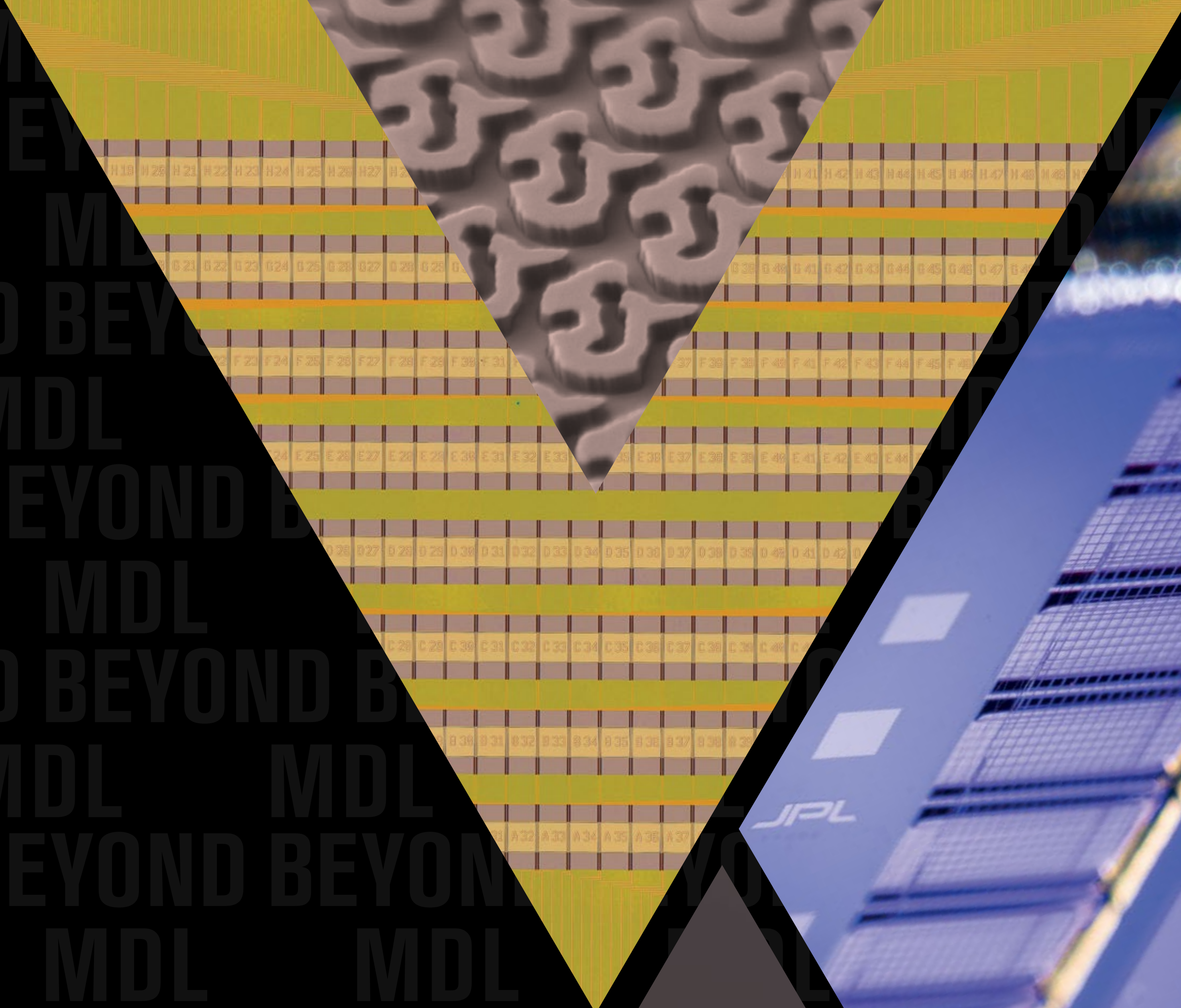

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