National Aeronautics and
Space Administration

RISING TO THE CHALLENGE & REACHING FOR THE FUTURE.

Jet Propulsion Laboratory
California Institute of Technology

MICRODEVICES LABORATORY
2021 | ANNUAL REPORT

PERSEVERANCE AT MARS WITH MDL DEVICES

PERSEVERANCE LANDED ON MARS IN 2021;

MDL HAD HELPED WITH 16 CAMERAS, 2 INSTRUMENTS AND 10.9 MILLION NAMES ETCHED ON 3 SILICON CHIPS.

PIXL

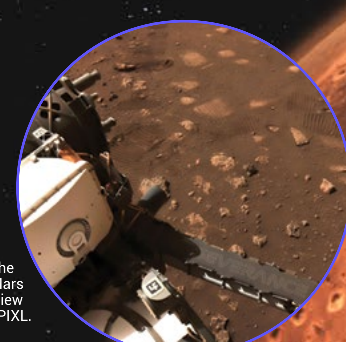
The Planetary Instrument for X-Ray Lithochemistry (PIXL) produces high-resolution (≈ 100 µm) maps of Mars rock elemental composition by focusing an X-ray spot on the rock, detecting the resulting X-ray fluorescence, then scanning the X-ray spot across the rock. The resulting elemental maps can be used to analyze geology as well as to search for fossilized evidence of past life. Once placed at a rock by the rover arm, PIXL must operate autonomously to focus its X-ray spot and to avoid collision with the rock. To measure distance to the rock, two structured light illuminators (SLIs) produce patterns of laser spots on the rock, which are detected with a camera, resulting in a distance determination at the location of each laser spot.

PIXL utilizes two SLIs to meet the divergent requirements for measuring the X-ray interception location and for hazard avoidance. The dense SLI has a 5×3 spot grid and 4° spot separation, and the sparse SLI has a 7×7 spot grid and 9° spot separation.

The structured light (patterns of laser dots) is produced with a diode laser, a focusing lens, and a custom grating. There are no commercially available diffraction gratings that can create the needed grid patterns, so custom diffraction gratings were designed and manufactured by Daniel Wilson and Richard Muller at the JPL Microdevices Laboratory (MDL). These computer-generated holographic gratings were patterned in polymer using electron-beam lithography, then etched into fused silica substrates (7 mm diameter × 1 mm thick, no coatings). Each grating is a periodic array of cells composed of square pixels with depth patterns designed to diffract the 830 nm laser beam into the desired spot array. The pixel patterns were designed utilizing a variant of the iterative Fourier transform (Gerchberg-Saxton) algorithm. A binary (two-level) design was chosen so that the gratings could be fabricated with a single electron-beam patterning step followed by a single fused silica etch step. The optimal etch depths were determined using a rigorous electromagnetic simulation. The 3×5 spot grating cell is a 20×20 array of 0.6 micron pixels. The 7×7 spot grating cell is a 34×34 array of 0.16 micron pixels.

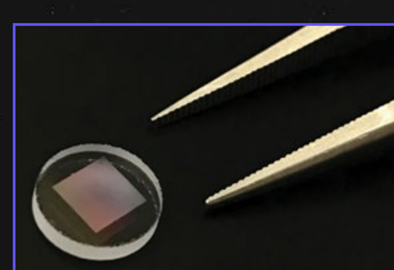
PIXL'S ACRONYM

ALLUDES TO PIXEL, THE SMALLEST DIGITAL POINT IN AN IMAGE. THE PIXEL IS AT THE HEART OF IMAGE PROCESSING AND DIGITAL IMAGES, FROM SPACE TELESCOPE PICTURES TO ROVER "SELFIES."



This image was taken during the first drive of the Perseverance rover on Mars on March 4, 2021. This view provides a good look at PIXL.

PIXL is equipped with light diodes circling its opening to take pictures of rock targets in the dark.



Diffraction grating on glass substrate.

LOOKING FOR SIGNS OF PAST LIFE

SHERLOC

The Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) produces high spatial resolution maps of chemicals and organic material found on Mars. SHERLOC combines fluorescence and Raman spectroscopy with microscopic imaging to analyze surface material to better understand the history of the aqueous environments recorded in the rocks of Jezero crater and to search for potential biosignatures.

SHERLOC imaging consists of two microscopic cameras, the Autofocus and Context Imager (ACI), and the Wide-Angle Topographic Sensor for Operations and eNgineering (WATSON). These subsystems obtain high spatial resolution images of geological targets to identify grain-scale structure and texture.

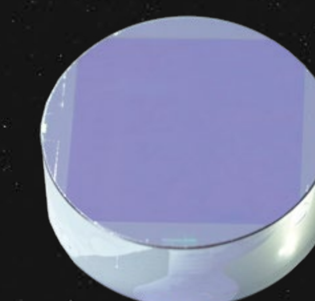
SHERLOC spectroscopy enables high-sensitivity detection, characterization, and spatially resolved correlation of trace organic materials. SHERLOC's 248.6 nm deep UV laser generates a 100 µm-diameter spot. Photons generated by Raman scattering and fluorescence emission are collected and spectra are downlinked to Earth for analysis. Knowledge of where the laser is pointed allows for mineral and compositional maps to be generated and overlain on images.

The instrument's unique diffraction grating was written via electron-beam lithography (EBL) in MDL at a very high groove density of 4200 grooves/mm. The zeroth-order diffraction is dumped into an angled port to minimize stray light. The first-order beam is diffracted with high efficiency (nearly 60%) onto a convex aspheric mirror, and then onto a concave spherical mirror that focuses the spectral signal across the long axis of the 512-by-2048 pixel e2v 42-10 SCCD. The spectral signal is projected as a curved line in order to separate the lower intensity Raman photons from the more intense fluorescence region.

An overarching theme of past and future Martian exploration focuses on characterizing its aqueous history, determining its habitability potential, and searching for evidence of life. The mineral and organic maps generated by SHERLOC will be combined with measurements from Perseverance's instrument suite to understand the geological history and context of rocks and regolith. This will enable the coring and caching of astrobiologically relevant samples for eventual return to Earth as part of the Mars Sample Return (MSR) campaign.

SHERLOC is one of the instruments aboard Perseverance located on the end of the rover's robotic arm (inset). The instrument's main tools are spectrometers and a laser, but it also uses an integrated "context" macro camera to take extreme close-ups of the areas that are studied.

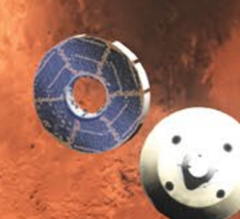
JEOL JBX 9500FS e-beam lithography system.



E-beam fabricated ultraviolet grating for Mars 2020 SHERLOC.

MDL IS ONE OF THE FEW FACILITIES WITH STATE-OF-THE-ART NANOLITHOGRAPHY CAPABILITY AND EXPERTISE

AND DEVELOPED NON-STANDARD E-BEAM FABRICATION TECHNIQUES TO REALIZE UNIQUE COMPONENTS AND DEVICES FOR JPL'S MOST CHALLENGING INSTRUMENT DESIGNS FOR NASA AND NON-NASA MISSIONS.



Perseverance Rover Decelerating in the Martian Atmosphere (Illustration).

This panorama, taken on February 20, 2021, by the Navigation Cameras (Navcams) aboard NASA's Perseverance Mars rover, was stitched together from six individual images after they were sent back to Earth.

THROUGH THESE 'EYES'

CAMERAS

The Mars 2020 Perseverance Rover has a total of 23 cameras, and 16 of these cameras were developed and delivered by the Jet Propulsion Laboratory's Flight Instrument Detector and Camera Systems Group in the Microdevices and Sensor Systems Section. These include 9 engineering cameras: 2 navigation cameras (Navcam), located on the remote sensing mast, 6 hazard avoidance cameras (Hazcam), located on the front and rear of the rover and 1 sample cache camera (Cachecam), located in the sample caching system vision station.

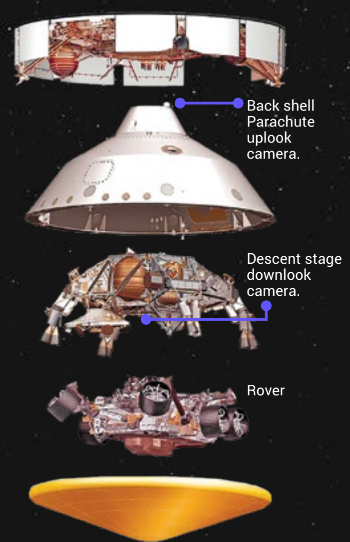
The Mars 2020 Navcams and Hazcams include three significant improvements over previous Mars rover cameras. The first is an upgrade to a red/green/blue (RGB) color CMOS detector that will provide better contextual imaging than the previous monochrome engineering cameras. The second is cameras with wider fields of view, improving the quality of mosaics and increasing downlink efficiency. The third is cameras with finer pixel scale (mrad/pixel) that are able to resolve more detail than previous Mars rover cameras.

Navcams are used to survey the terrain 360 degrees around the rover and for traverse planning, science target identification and selection, robotic arm operation, and rover auto-navigation.

They are also used to document the state of the rover using images of rover hardware and to determine the rover orientation relative to known surface features or the sun. Hazcams are used to image the areas immediately in front of and behind the rover, particularly areas not observable by the Navcams. Hazcams also support robotic arm operation, rover navigation and inspection of the wheels their contact with the terrain. Cachecam is a fixed-focus imager used for sample inspection and documentation by taking images of the sample material during caching operations. These images will also be used to document the tube contents prior to sealing and to inform science on the sample integrity.

The remaining 7 cameras, shown in the image below, comprise the EDLCAM system including four camera types. Three Parachute Uplook Cameras (PUCs) were used to monitor parachute deployment. A Descent stage Downlook Camera (DDC) was used to record the rover's descent from the skycrane, while the Rover Uplook Camera (RUC) simultaneously recorded the descent stage as seen from the rover. The Rover Downlook Camera (RDC) imaged Mars as the rover touched down onto Mars. Video from the EDLCAM system was relayed to Earth in the subsequent sols after the rover was safely on Mars. The system also contained 2 ruggedized USB3 hubs used to network the cameras to a custom interface board that included a single-board computer and solid-state storage disk.

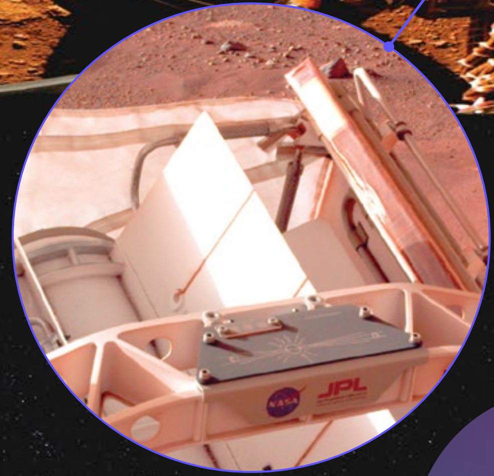
EDL cameras' view of descent and touchdown.



HazCam's first color look at Mars.

EDLCAM System.

16 CAMERAS WERE DEVELOPED AND DELIVERED BY MDL.



A plate was designed to include the 3 chips. Within the Sun's rays is a message reading "explore as one" in Morse code.

The 10.9 million names were duplicated in 24 places on a silicon wafer before being diced up into chips.

GAINING IMMORTALITY

SILICON CHIPS

In keeping with a JPL tradition that started with the StarDust spacecraft in the late 1990s and has been continued by many other missions, MDL was once again asked to use its electron-beam lithography capability to fabricate millions of names submitted by the public written onto silicon chips for the Perseverance Rover. NASA's Mars public engagement campaign created a "Send Your Name to Mars" website which received worldwide participation and collected millions of names in more than 100 modern and historic scripts. MDL's electron-beam fabrication team was responsible for converting bitmap images into 15 micrometer high text and using the electron-beam system to write the submitted names onto three 8-mm square silicon chips. Using a Ti-Pt deposition and lift-off process, they created lines of text some smaller than 75 nanometers.

The chips were placed on a plate commemorating NASA's "Send Your Name to Mars" campaign and were installed on the Perseverance Mars rover on March 16, 2020, at NASA's Kennedy Space Center in Florida. The chips feature the names of the 10,932,295 people who participated, along with the essays of the 155 finalists in NASA's "Name the Rover" contest. The huge international interest and web participation in the "Send Your Name to Mars" campaign led to two of the eight Webby Awards that NASA received in 2020, one for Best Social Community Building and Engagement, as well as the People's Voice award in its category.

10.9 MILLION NAMES, NOW ON MARS.

MDL used an electron beam to stencil the submitted names onto silicon chips. Three different chips were needed to fit all of the text.

LEADERSHIP

The Microdevices Lab at JPL is a world-class asset whose staff continues to invent, develop, and deliver novel devices to enable new instruments and missions for NASA. This year has been challenging but successful for MDL. During the COVID-19 pandemic, the leadership team has ensured our teams' safety while they continued to deliver and advance critical devices for a broad spectrum of suborbital, ground-based, and research and development projects, though at a slower, safety-protocol-driven pace. For example, MDL successfully delivered science-measurement-enabling devices for the Coronagraph Instrument on the Nancy Grace Roman Space Telescope, for the Mapping Imaging Spectrometer for Europa (MISE), and for the Earth Surface Mineral Dust Source Investigation (EMIT).

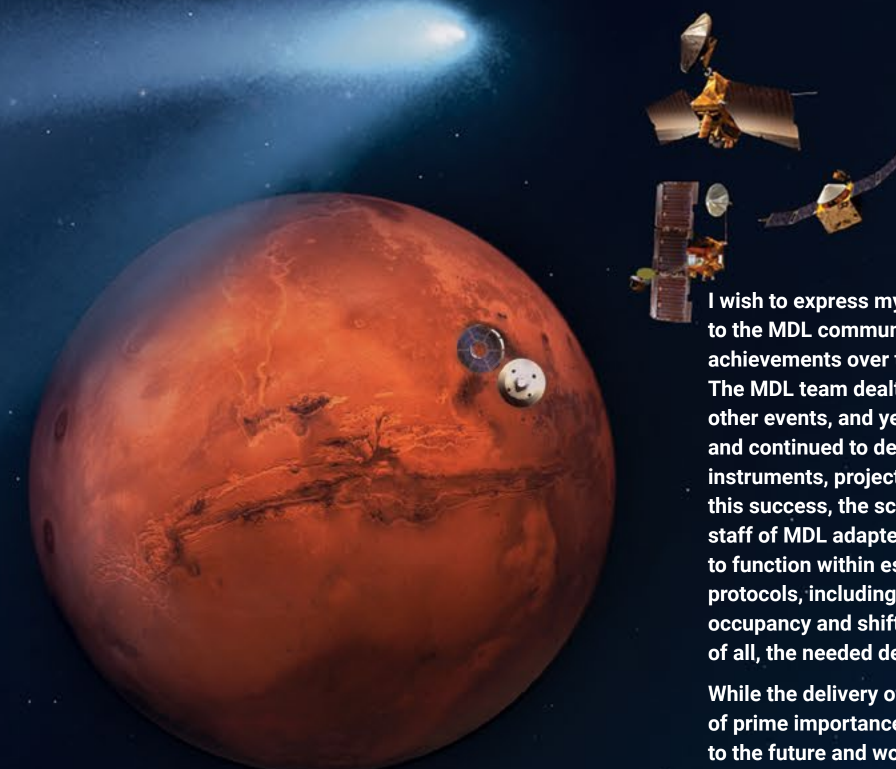
The devices MDLproduces support missions spanning the Astrophysics, Planetary Science, and Earth Science Divisions of NASA. Looking forward, MDL devices and contributions will be important in upcoming projects, such as the Carbon Plume Mapper (CPM) and the Venus Tunable Laser Spectrometer on the DAVINCI NASA Discovery mission, led by the Goddard Space Flight Center.

JPL continues to invest in the people, tools, and facilities of MDL to assure that the next generation of devices and capabilities will be ready to support the future needs of NASA and our nation. This annual report records an important snapshot of the many activities at MDL and highlights the diversity of people and projects involved at all levels of technology development, from early concepts to delivery for spaceflight missions. MDL truly is a crown jewel for JPL, NASA and our nation.

LARRY JAMES

Deputy Director, Jet Propulsion Laboratory

MDL TRULY IS A CROWN JEWEL FOR JPL, NASA AND THE NATION.



I wish to express my awe of and gratitude to the MDL community for their exceptional achievements over this most difficult past year. The MDL team dealt with COVID-19, wildfires, and other events, and yet they persevered, succeeded, and continued to deliver enabling devices for NASA instruments, projects, and missions. To achieve this success, the scientists, technologists, and staff of MDL adapted and found new ways to function within essential yet challenging safety protocols, including greatly reduced cleanroom occupancy and shift work. Thanks to the efforts of all, the needed devices have been delivered.

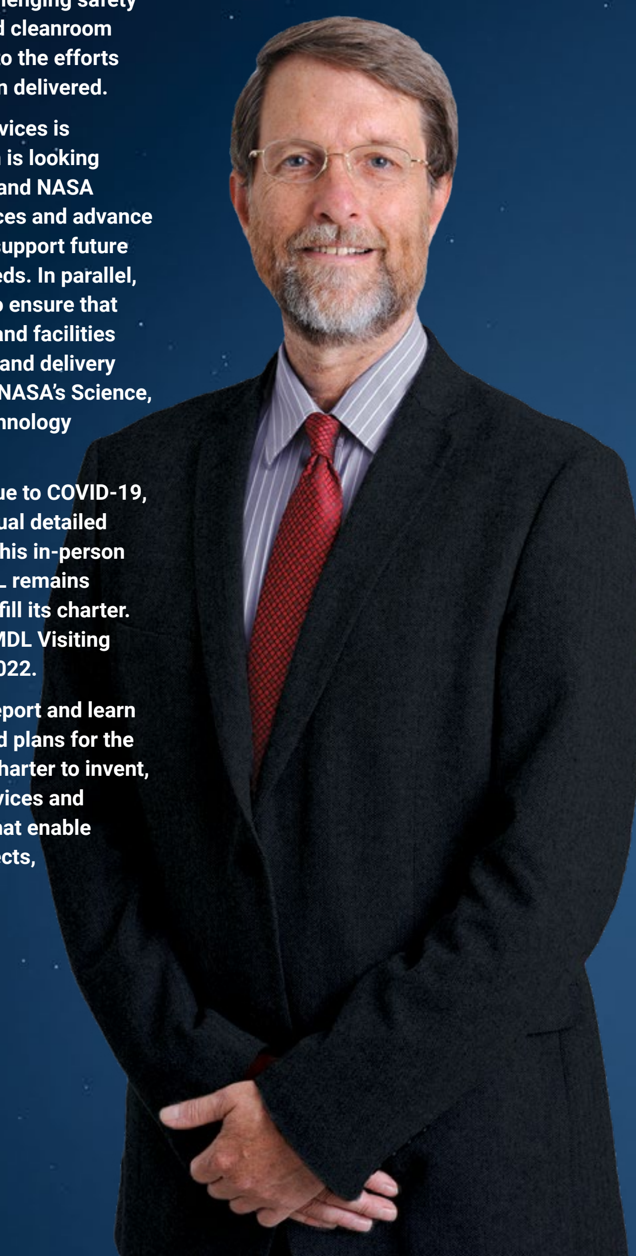
While the delivery of spaceflight devices is of prime importance, the MDL team is looking to the future and working with JPL and NASA customers to conceive of new devices and advance lower-technology-level devices to support future NASA missions and technology needs. In parallel, MDL leadership is looking inward to ensure that MDL is investing in the equipment and facilities needed for the future development and delivery of unique and enabling devices for NASA's Science, Human Exploration, and Space Technology Directorates.

I would like to note that this year, due to COVID-19, we have decided to delay the biannual detailed review of the Visiting Committee. This in-person review functions to assure that MDL remains state of the art and continues to fulfill its charter. We look forward to convening the MDL Visiting Committee in the late summer of 2022.

I invite you to explore this annual report and learn more about our recent activities and plans for the future, which are aligned with our charter to invent, develop, and deliver novel microdevices and critical microdevice technologies that enable new capabilities, instruments, projects, and missions for NASA.

ROBERT GREEN

Director, Microdevices Laboratory



RISING TO THE CHALLENGE & REACHING FOR THE FUTURE

For the past 31 years, through the dedication and hard work of many talented scientists, technologists, and research staff, JPL's Microdevices Laboratory (MDL) has made fundamental contributions to diffractive optics, detectors, nano- and microsystems, lasers, focal planes with breakthrough sensitivity from deep UV to submillimeter, life detection in extreme environments, and MEMS. Through this research and development, MDL has produced novel, innovative, and unique components and subsystems enabling remarkable achievements in support of NASA's missions and other national priorities. We are excited to have been a part of this important work and look forward to many years of continued success. Visit us online at **microdevices.jpl.nasa.gov**

CONTENTS

CHARTER

MDL is a specialized laboratory within JPL that invents, develops, and delivers novel microdevices and critical microdevice technologies not available elsewhere that enable new capabilities, instruments, and missions for JPL and NASA.

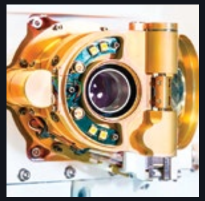
ROLE & VISION

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.

OCO3: Slits

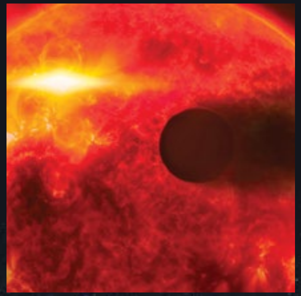
Roman Coronagraph Instrument (CGI): HLC or PIAACMC designs with e-beam gray scale and MDL black silicon; and deformable mirror metallization/lithography.

PREFIRE: Detector



Mars2020, SHERLOC: Gratings

Mars2020, PIXL: Spot-array generator gratings



SAFFIRE (CPM): Lasers for Combustion Product Monitor

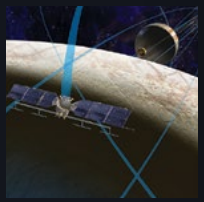
SPARCS: UV spectrometer

CIRAS: MWIR Focal Plane Array and dewar cooler assembly

HyTI: LWIR Focal Plane Array and dewar cooler assembly

CASE: H2RG/SIDECAR space flight packaging

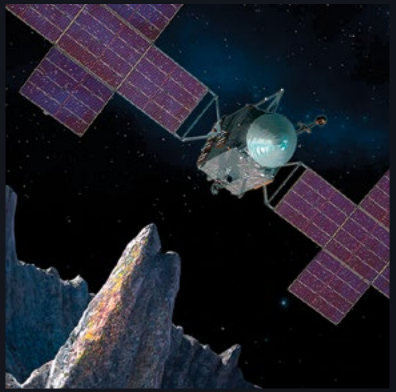
JWST, NIRCam Coronagraph: E-Beam fabricated occulting spots



Europa MISE: Grating, slit, zero-order-light-trap

MDL WORKS BROADLY SUPPORT JPL PROJECTS

EUCLID: Sidecar Electronics Correction



Psyche DSOC: Detectors (SNSPDs)

ISS SAM: Mass Spectrometer (GCMS)

ISS ECOSTRESS: Calibration targets, SWIR bandpass filter

HVM^3: Lunar Trailblazer

Radiation Budget Instrument: Thermopile Detectors

EMIT: Grating, slit, stray light control

APPROACH

To achieve the outcomes described in its Charter, MDL uses the latest science and technology to invent and deliver novel microdevices and capabilities, sometimes partnering with world leaders in various specialisms to infuse their skills and knowledge into JPL. These developments enable new opportunities for NASA missions to better understand the Earth and space.

MDL started with an exceptional and diverse group of scientists, technologists and staff who were able to use their talents to fulfil its mission. The continuation of the success was only and can only be achieved by attracting people with the same qualities to ensure a sustainable future for the Laboratory. The products of MDL efforts must all show their utility, whether they be components of an instrument or an instrument itself. These devices then form an integral part of the payload for a JPL or other NASA mission and therefore must be of flight quality.

Palomar Observatory at Night under the Milky Way.
Credit: Phillip Colla / Oceanlight.com

2020 MDL HIGHLIGHTS

MDL is at the forefront of the innovation and implementation of new technologies to inspire and enable cutting-edge research at JPL and throughout NASA.

This image taken with the NASA/ESA Hubble Space Telescope showcases the emission nebula NGC 2313. Emission nebulae are bright, diffuse clouds of ionized gas that emit their own light.

12 ROMAN OBSERVATORY CORONAGRAPH

NASA's Nancy Grace Roman Space Telescope, top-ranked large space mission in the 2010 Decadal Survey of Astronomy and Astrophysics, is due to launch in the mid 2020s. It has both a wide field of view and superb resolution to look at the universe but also carries the JPL Coronagraph Instrument to give unprecedented opportunities for imaging exoplanets.

14 ASTHROS BALLOON MISSION

Tentatively scheduled to launch in 2023 from NASA's Long Duration Balloon Camp near McMurdo Station in Antarctica, ASTHROS will aim to fly for 21 to 28 days an altitude of about 130,000 feet—high enough to observe wavelengths of light blocked by Earth's atmosphere.

16 LUNA-ICE MISSION

NASA is interested in investigations that maximize basic and applied science and technology demonstrations at different lunar locations, as well as individual investigation components that would be valuable at multiple locations.

18 TLS FOR VARIOUS MISSIONS

Essential components of the Mars Tunable Laser Spectrometer (TLS) originated at MDL, and MDL will also be responsible for developing lasers and detectors for the recently selected Venus probe Discovery mission. TLS is still operating on Mars, but applications on Earth and other planets no doubt lie in its bright future.

20 WATER QUALITY FOR HUMAN SPACEFLIGHT

Future human space exploration and current occupation of the International Space Station (ISS) require that primary necessity for life, water. Technologies pioneered on the ISS will be developed further for future space exploration to the Moon and Mars and include the process of recycling water.

CORONAGRAPH INSTRUMENT

MDL ENABLES NANCY GRACE ROMAN SPACE TELESCOPE

ADVANCING THE ENGINEERING AND TECHNICAL READINESS OF KEY CORONAGRAPH ELEMENTS NEEDED FOR FUTURE MISSIONS TO DETECT AND CHARACTERIZE EARTHLIKE PLANETS.

This NASA orbiting observatory is designed to answer essential questions about dark energy, exoplanets and infrared astrophysics. The Nancy Grace Roman Space Telescope Coronagraph Instrument is one of two instruments on the Telescope, and it could not have been proposed or built without critical MDL technologies. The Coronagraph Instrument will perform high-contrast imaging and spectroscopy of individual nearby exoplanets.

Originally called the NASA Wide Field Infrared Survey Telescope (WFIRST), the Roman Space Telescope was built for two very ambitious aims. The first is to map the distribution and structure of matter throughout the universe to help understand dark energy. The second is to directly observe and conduct spectroscopy on very faint images of exoplanets orbiting distant stars. The Roman Observatory has two main components: the Wide Field Instrument (WFI) and the Coronagraph Instrument, a technology demonstration being built by JPL.

JPL's Coronagraph Instrument will enlighten the exoplanet community by blocking the light emitted by a star so that the light reflected by the planet can be seen clearly. Instead of using a disc to physically block the star's light, optical interference technology will be used, but this technology can result in residual starlight artifacts caused by distortions and diffraction effects from the series of mirrors employed and their edges. However, by using flexible, deformable mirrors controlled by autonomous software, the residual starlight artifacts can be removed, allowing the direct imaging of planets having about one hundred billionth the light intensity of their stars. In fact, the Coronagraph Instrument has two systems, the Hybrid Lyot Coronagraph (HLC) and the Shaped Pupil Coronagraph (SPC), which are both enabled by MDL technology. The Coronagraph Instrument will be the first advanced coronagraph to be flown and is 1,000 times more capable than previous coronagraph instruments.

The mission received its new name in May 2020 to honor an extraordinary woman, Dr. Nancy Grace Roman. Dr. Roman joined NASA in early 1959, only six months after its formation. She was the first female executive at NASA, was appointed the first Chief of Astronomy and subsequently held many other significant senior posts. It was most appropriate that this mission was renamed for her since during her long career, one of her major achievements was not scientific, but political: Getting the Hubble Space Telescope approved by the U.S. Congress. Because of this accomplishment, she was known to her colleagues as "The mother of Hubble." She eagerly followed the successes Hubble produced, and when asked what she thought was its most interesting breakthrough, she replied, "Dark energy," which, as one of the major aims for this follow-on mission to Hubble, is another very fitting reason for the name change.

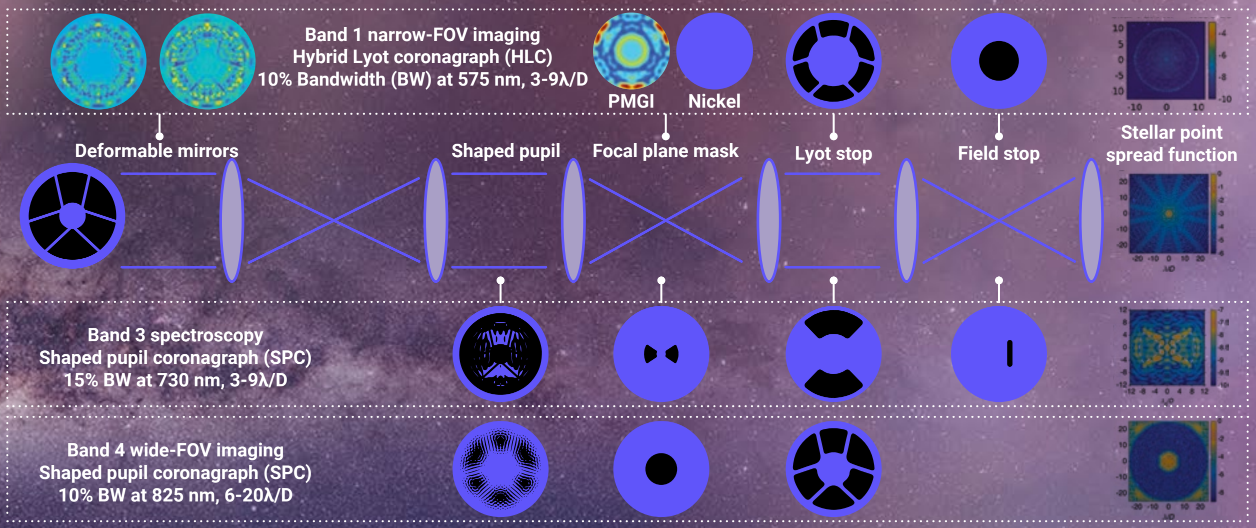
The continued successful progress of the Coronagraph Instrument has only been possible through foresight and prescient investment in facilities at JPL and especially MDL. A coronagraph was included in the WFIRST mission proposal in 2013. The Coronagraph Instrument test bed was completed in 2016, which allowed the all-important demonstration of its flight operation in a test bed environment in 2019. MDL's contributions include many components fabricated with electron beam technologies, without which the Coronagraph Instrument could not function. There will be continued MDL involvement and excitement in this most important mission until its launch in the mid 2020s.

ENGINEERING DEVELOPMENT UNIT (EDU)

To pursue development of the Coronagraph Instrument, many activities had to proceed in parallel even though sequential operation might have been more logical. Therefore, the Engineering Development Unit (EDU) camera was used. In many respects, its specifications are identical to those of the unit to be used, but it differs because it is not necessarily built with flight-qualified or flight-qualifiable parts and is not subjected to quality assurance checks. Thus, the EDU camera allows system development and tests. It has been operating and enabled a series of camera Critical Design Reviews (CDRs) for sensor, electronic and mechanical elements to be passed.

EDU chip.

EDU sensor/ mirror sub-assembly.

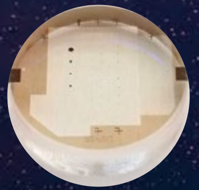


An illustration showing the key CGI coronagraphic mask designs in a simplified conceptual beam train starting with the Roman Space Telescope RST pupil obscuration. Images not to scale.

HYBRID LYOT CORONAGRAPH (HLC)

The French astronomer Bernard Lyot invented the coronagraph in 1939 to enable him to look at the Sun's corona without having to wait for a total eclipse. In his system, the light entering the pupil (aperture) of the telescope is brought into focus on an opaque spot, the focal plane mask, instead of directly onto a camera or detector. Another lens images the light that has not been occluded from the edges and a small part of the central area onto a camera or detector after further elimination of internally scattered light by a component called a Lyot stop. For the best possible performance, the Roman Telescope uses a hybrid device with an external occulting disc and a Lyot system. The HLC has an occulting mask, a partially transmissive nickel disc overlaid with a radially and azimuthally varying dielectric coating; and a Lyot stop, an annular mask that blocks the telescope pupil edges and struts. It also has a mask with an array of field stops that will help further reduce the detection of diffracted starlight. Thus, the approach initially taken to block out the central light from one star, our Sun, will be used for many other stars.

HLC Lyot stop.

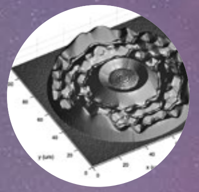


Focal plane mask.

SHAPED PUPIL CORONAGRAPH (SPC)

An SPC makes the pupil edges fainter by absorbing light, either with a continuous or "binary" (shaped pupil) mask. The Coronagraph Instrument's HLC and SPC masks differ, but either can be used in the Coronagraph Instrument because both use the same architecture. There are two SPC modes, each with its own set of masks: one for spectroscopy at small working angles and the other, the SPC-Wide Field of View (SPC-WFOV), for imaging extended objects (such as circumstellar debris discs). SPCs require myriad fabrication approaches to meet the required range of specifications, which include precise shapes, very-small-scale island features, ultra-low-reflectivity areas, uniformity, wave front quality, achromaticity, and other features. The Coronagraph Instrument SPC uses a pupil plane and image plane masks fabricated by combining three MDL competencies: electron beam lithography, deep reactive ion etching, and the fabrication of black silicon.

SPC black silicon mask.

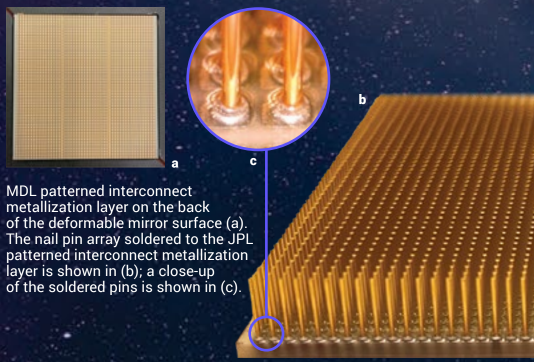


Mask profile measured using atomic force microscopy.

DEFORMABLE MIRROR

The Coronagraph Instrument relies on a pair of deformable mirrors to actively control the complex incoming wavefront from an observed exoplanet system to create a high-contrast dark field of view, handle static telescope wavefront errors and compensate for thermal drift in the telescope. The active wavefront control, together with advanced light blocking technologies, will allow for the direct imaging of exoplanets by cancelling the bright light from the host star. The wavefront is controlled by deforming the mirror surface to a precision of less than the diameter of an atom by using 2,300 actuators in a module block attached to the back of the mirror. The module consists of platinum electrodes embedded in a ceramic electrostrictive material. The modules are manufactured by Northrup Grumman—AOA Xinteics.

MDL patterns and deposits the metallization layer on the ceramic that ensures electrical contact to the platinum electrodes in each of the actuators within the module. The nail pins are soldered directly to these metal contact pads by a local business, Topline. Each actuator is moved by applying a voltage to a corresponding nail pin attached to the back side of the electrostrictive modules. Flex print cables plug into the nail pins and connect the deformable mirror to the drive electronics.



MDL patterned interconnect metallization layer on the back of the deformable mirror surface (a). The nail pin array soldered to the JPL patterned interconnect metallization layer is shown in (b); a close-up of the soldered pins is shown in (c).

SUBMILLIMETER DEVICES

FROM ANTARCTIC COLD TO THE HEAT OF A NEWLY BORN STAR

ASTHROS is a high-altitude balloon mission to study key tracers of star formation in the far-infrared.

One of the main science goals of the Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter wavelengths (ASTHROS) is to provide new information about stellar feedback in the Milky Way and other galaxies, a process in which stars either accelerate or decelerate the formation of new stars in their galaxy. Stellar feedback has played a critical role in the evolution of galaxies throughout the universe's history. Without it, the available gas and dust in galaxies like our own would have coalesced into stars long ago, and no new star formation would take place. To investigate stellar feedback, ASTHROS will need to identify and measure certain chemical species in gas and dust clouds in the 1.4 terahertz (THz) to 2.7 THz range and to measure precisely the density and dynamics of those chemical species. A key objective for ASTHROS will be mapping two specific nitrogen ions, only just visible in the fine structure of the spectrum at ~1.46 THz and ~2.46 THz, that are formed by the processes that drive stellar feedback. This mapping data will enable astronomers to create 3D maps of star-forming regions, as well as of the density and movement of the gas, to learn about the influence of stellar feedback.

ASTHROS will observe a target of opportunity, TW Hydrae, a young star surrounded by a wide disk of dust and gas where planets may be forming. With its unique capabilities, ASTHROS will measure the total mass of this protoplanetary disk and show how this mass is distributed throughout. These observations could reveal places where the dust is clumping together to form planets. Learning more about protoplanetary disks could help astronomers understand how different types of planets form in young solar systems.

Tentatively scheduled to launch in December 2023 from NASA's Long Duration Balloon Camp near McMurdo Station in Antarctica, ASTHROS will aim to fly for 21 to 28 days an altitude of about 130,000 feet (40 kilometers)—high enough to observe wavelengths of light blocked by Earth's atmosphere. When fully inflated, the 40-million-cubic-foot helium balloon will be about 400 feet (150 meters) wide, or roughly the size of a football stadium. The ASTHROS telescope features a lightweight 2.5-meter antenna to collect far-infrared light. The telescope is tied for the largest ever to fly on a high-altitude balloon. A gondola beneath the balloon will carry the telescope, instrument and other hardware. The telescope's detectors must be cooled down to 4 K. While many balloon and space missions carry liquid helium to keep instruments cold, this strategy limits the mission lifetime based on how much helium is on board. Instead, ASTHROS will use a cryo-cooler powered by electricity from its solar panels.

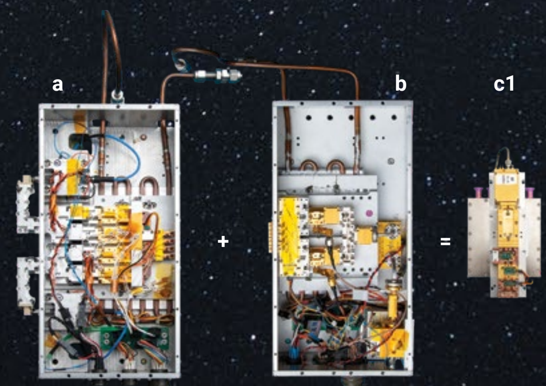
To achieve its scientific objectives, ASTHROS must make observations with the highest possible resolution. Consequently, the instrument consists of two high-spectral-resolution heterodyne receivers covering the 1.4-2.1 THz band and the 2.4-2.7 THz band. Each receiver channel consists of two dual-polarization 4-pixel receivers. To meet the challenging technological needs of the mission, ASTHROS heavily relies on two MDL core competencies: superconducting hot electron bolometer (HEB) submillimeter-wave technology and Schottky-diode-based frequency multiplied local oscillator submillimeter-wave sources. To increase the scientific return of far-infrared missions and capture all the key tracers of star-forming regions, a new generation of these sources and receivers has been developed to increase the frequency coverage by a factor of two or more with respect to previously flown systems. Moreover, balloon-borne missions are high risk, especially when it comes to accelerated integration and test phases in remote environments like Antarctica. Therefore, increased device performance to maximize margins is a must. The new generation of frequency multipliers produced at MDL have considerably higher performance than the previous generation flown in missions such as the Stratospheric Terahertz Observatory (STO-2) in 2016.

BALLOON-BORNE TELESCOPES

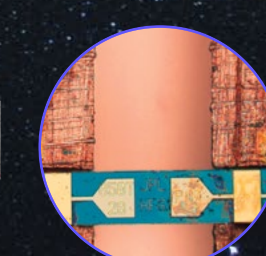
OPERATING IN THE STRATOSPHERE OFFER SUBSTANTIAL RETURNS WITH SUBSTANTIALLY LOWER COSTS AND LEAD TIMES.

The local oscillators produced for ASTHROS have output power levels approximately five times higher than the previous state of the art. In addition, a novel (patent pending) technique has been applied to increase the RF bandwidth by a factor of two, making it possible to capture many species with just one receiver channel. This is a significant step forward for future space missions in the far-infrared.

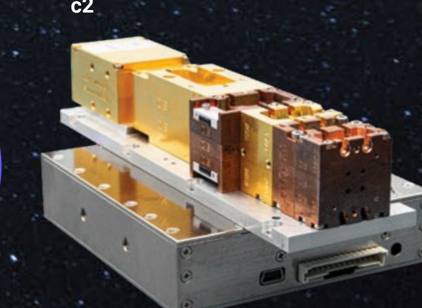
The superconductor mixer device and semiconductor frequency multiplier technology have been developed by MDL over many years with multiple sources of support, including several NASA and JPL Research and Technology Development awards to advance the performance of these devices. It will be exciting to look forward over the next few years to see the scientific return on these investments.



A comparison between the new generation 4-pixel local oscillator source developed at JPL for ASTHROS and the previous generation flown on STO-2 (2016). The ASTHROS unit represents a more than twofold increase in frequency coverage and a more than fivefold reduction in mass, size and power consumption.



MDL-produced GaAs Schottky-based frequency multiplier device used in the ASTHROS band 2 LO source.

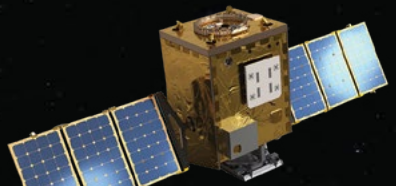


a) STO-2 4-pixel 1.9 THz LO (100 W, 5Kg).
b) STO-2 4-pixel 1.46 THz LO (70 W, 5Kg).
c1) JPL 4-pixel integrated 1.35-2.07 THz LO (27 W, ~300g). Side view of the assembly (c2).

Background image: Artist's concept showing the stratospheric ASTHROS flight over Antarctica (planned for 2023). ASTHROS will produce the first high-spectral-resolution images of the [NII] 122 μm line, which is mostly obscured by the atmosphere, even at Stratospheric Observatory for Infrared Astronomy (SOFIA) altitudes, and can only be observed efficiently at balloon altitudes or from space.

THERMOPILE DETECTORS

GETTING THE MOON'S WATER OUT OF THE SHADOWS



Lunar Trailblazer will detect signatures of water ice in reflected light, and it will pinpoint the locations of micro-cold traps less than a football field in size. Credit: Lockheed Martin

Three linked missions represent the past, the present and future enabled by successive developments in MDL technology.

The mission representing the past was the Indian Space Research Organisation's Chandrayaan-1 mission. This was India's first deep space mission and was an ambitious enterprise comprising both a lunar orbiter and an impactor. The mission was a spectacular success in that the Moon Mineralogy Mapper (M³) instrument not only produced a map of the mineralogy of the Moon but also detected the presence of water over most of the Moon's surface, especially at the poles. This surprising initial discovery of water on the Moon's surface reinforced the unconfirmed measurements of the very thin lunar atmosphere by the impactor while on its way to the surface. The heart of the M³, an imaging spectrometer, was a convex diffraction grating designed and fabricated at MDL. The grating covered the spectral range from violet at the shorter-wavelength end of the visible spectrum through the mid-infrared and was designed to produce a similar high-quality signal throughout the range.

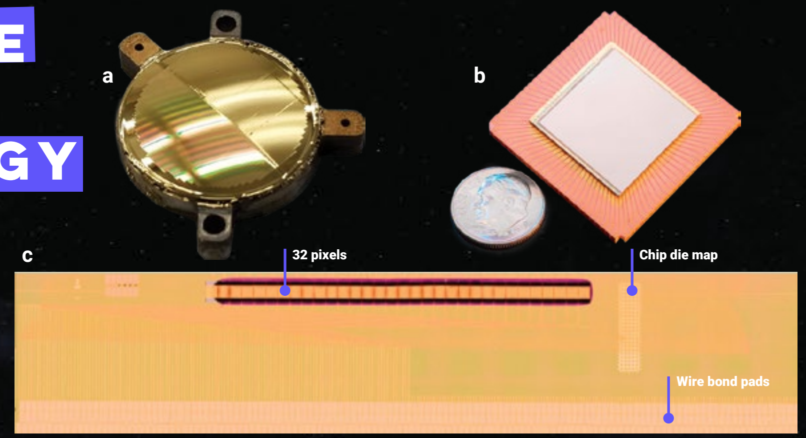
The present and near future are represented by the NASA Lunar Trailblazer mission, which also depends heavily on MDL technology. The mission was selected for further development in June 2019, and its objective is to investigate in much greater detail the outstanding discovery of water on the Moon. In November 2020, after more than a year of further concept development and many reviews, Lunar Trailblazer was selected by the Small Innovative Missions for Planetary Exploration (SIMPLEx) program to begin the final hardware design and build, aiming for a 2022 launch. The enabling MDL technology for this mission is the HVM³, an imaging spectrometer developed from the JPL Ultra Compact Imaging Spectrometer (UCIS), which will exceed the spectral range and wavelength resolution of the M³. It will allow proper correction for the effects of temperature on the measured spectra. Among other aims, the mission will look at the geographical variability of water content on the lunar surface and temporal changes between night and day, which can be used to chart the cycle of water vapor release to the atmosphere and condensation back from it. The (uncertain) future is the possibility of even further development of the imaging spectrometer, but coupled with two other key, innovative MDL technologies as part of an *in situ* (rather than a remote observation) instrument. The instrument is the Lunar *In situ* Cold trap Explorer (Luna ICE), and its central feature is the Midwave- and Longwave-infrared Point Spectrometer (MLPS), which is enabled by three MDL technologies. These technologies are MDL's unique bi-faceted grating, barrier infrared detector (BIRD) technology, and thermopile detector technology; the two detectors (thermopiles and BIRDs) and their readout integrated circuits (ROICs) will be packaged into a compact format specifically developed to keep the two beams only 5 mm apart and will include a thermal control system to keep the BIRD at 140 K without cooling the thermopile detector. To achieve this compact packaging, the two detectors are on a common focal plane array (FPA) with zone thermal control. The high-operating-temperature BIRD and the uncooled thermopile detector measure different parts of the spectrum, namely infrared (1.75 – 3.5 μm) and longwave infrared (5.5 – 11 μm), respectively. Support from JPL validated the performance of the MLPS instrument and raised its overall technology readiness level to 6.

This preparation allowed the MLPS to be proposed in December 2020 to the Step 1 opportunity for the NASA Research Opportunities in Space and Earth Sciences (ROSES) program Payloads and Research Investigations on the Surface of the Moon (PRISM).

The PRISM program is ongoing, and NASA plans to continually launch payloads to the Moon. Thus, there will be additional opportunities for this technology to be included on a future lunar mission. Ideally, the Luna ICE instrument would land in Schrödinger crater near the Moon's south pole, where a substantial amount of the terrain is in permanent shadow. Among other objectives, the mission would investigate the possibility of the existence of long-term ice deposits and the water cycle in this very cold part of the Moon.

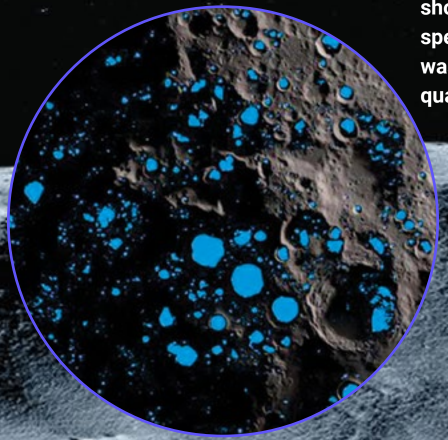
INNOVATIVE MDL TECHNOLOGY

CAN ENABLE MISSIONS TO MAKE UNPRECEDENTED SCIENTIFIC DISCOVERIES. THE TECHNOLOGY CAN BE REINCARNATED AND DEVELOPED FURTHER FOR LATER MISSIONS, SUCH AS SUCCESSIVE MISSIONS TO UNDERSTAND THE MYSTERY OF THE MOON'S WATER.



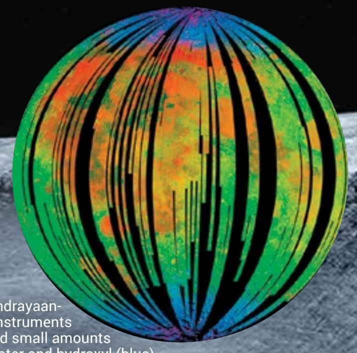
Three key technologies from MDL are used in the MLPS. (a) The bi-faceted grating. (b) A BIRD bonded to an SBF 193 ROIC sitting on a chip carrier.

(c) A 32-pixel thermopile array shown in a scanning electron microscope image. Only 22 of 32 pixels are used in the implementation.



Permanently shadowed regions (shown in blue) cover about three percent of the moon's south pole, and should be good places to find water ice.

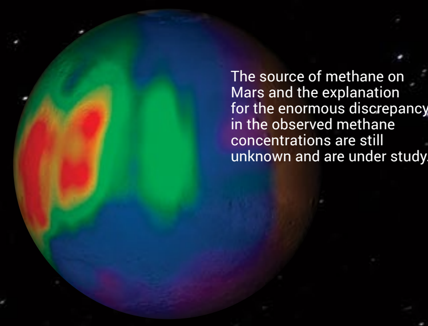
Commercial landers like this will carry science and technology payloads to the lunar surface, paving the way for NASA astronauts to land on the Moon by 2024.



Chandrayaan-1's instruments found small amounts of water and hydroxyl (blue) on the surface of the Moon.

TUNABLE LASER SPECTROMETER

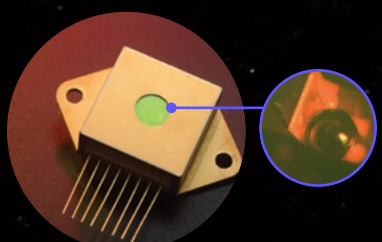
THE LIFE AND REBIRTH OF TLS



The source of methane on Mars and the explanation for the enormous discrepancy in the observed methane concentrations are still unknown and are under study.

ESSENTIAL COMPONENTS OF THE MARS TUNABLE LASER SPECTROMETER

originated at MDL, and MDL will also be responsible for developing lasers and detectors for the recently-selected Venus probe Discovery mission. TLS is still operating on Mars, but applications on Earth and other planets no doubt lie in its bright future.



A hermetically sealed package designed to house MDL mid-infrared semiconductor lasers, including the lasers to be used for the Venus Tunable Laser Spectrometer.

Although the Perseverance rover is actively looking for signs of past life on Mars, there is only one known habitable planet in the solar system: Earth. Our two neighboring planets, Mars and Venus, are of similar solid composition but are very different in terms of surface temperature and the presence of water. Mars has lost most of its atmosphere and is very cold, while Venus has a very dense atmosphere and is very hot. These are two large-scale natural laboratories, and if we could chart their different evolutionary paths, they could tell us why Earth is habitable and help understand which exoplanets might also be habitable. The isotopic ratios in stable species, such as the deuterium to hydrogen ratio D/H and $^{18}O/^{16}O$ in water, as well as $^{13}C/^{12}C$ and $^{18}O/^{17}O/^{16}O$ in carbon dioxide, are changed by the processes of evaporation and condensation and thus provide vital record of atmospheric and oceanic processes. On Mars, constant monitoring can identify the dynamic processes that might change the atmosphere between night and day or with the seasons. Of particular interest is the variation in the concentration of methane because of its possible association with organic matter and even biological processes. On Venus, detailing the atmospheric composition and chemistry may help us understand why Venus seems to represent a runaway greenhouse extreme. To achieve this understanding, very precise isotope measurements that can only be measured using laser spectroscopy are needed.

JPL's Tunable Laser Spectrometer (TLS) has already proven itself capable of undertaking such measurements over its eight years of operation on Mars. As part of the Sample Analysis of Mars (SAM) suite in the Curiosity rover, the 2-channel TLS uses infrared semiconductor lasers designed and fabricated at MDL specifically for sample analysis at the 2.78 and 3.27-µm wavelengths. These lasers make the key measurements of Martian gas abundance and isotope ratios, both in the atmosphere and as evolved from heating solid samples.

TLS has achieved noteworthy successes that have been reported in several papers in Science magazine and other journals. Findings include the detection of low background levels of methane on Mars at 0.4 parts per billion by volume (ppbv), which occasionally spike to higher levels, once as high as 20 ppbv during a two-hour ingest. Monitoring the sub-ppbv background level over eight years has revealed what appears to be a repeatable seasonal cycle in nighttime methane.

The day-night differences in Martian methane are fascinating. TLS reports an absence of methane during the Martian day. In other words, low background levels near 0.4 ppbv are seen only at night, when the low planetary boundary layer and convergent downslope winds at the Gale Crater cause methane from surface microseepage to be trapped at night. In concert with the mass spectrometer on SAM, the TLS measurements of D/H in water evolved

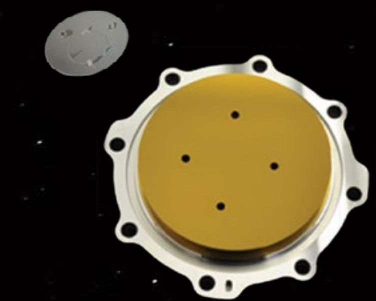
VENUS HOLDS THE KEY TO UNDERSTANDING EXOPLANETS

The proposed DAVINCI+ probe includes the JPL-built Venus Tunable Laser Spectrometer.

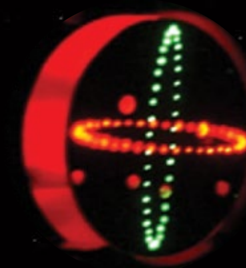
from rock pyrolysis show values that are only three times those on Earth (compared to six times those in the Martian atmosphere). These data indicate that at an earlier time, the Gale Crater region had significant liquid water, with a global equivalent layer of ~150 m in depth. Measurements of atmospheric CO2 isotope ratios on Mars at unprecedented accuracy of a few parts per thousand further show that the Martian atmosphere has changed in 4 billion years. The ^{13}C and ^{12}C results form a balance between atmospheric loss and carbonate formation, a key result for models of planetary evolution.

TLS has been performing perfectly on Mars, but instrument development has not stopped. In the last year, more progress has been made using MDL technology. Miniaturized versions of TLS instruments are going to the International Space Station (ISS) and are part of the NASA astronaut space suit and Orion respiratory monitor. Other developments have improved detection through NASA's PICASSO program, with a detector array coupled to an infrared-transmissive mirror to image all or part of the multipass spot pattern of the far mirror and record spectra for each pixel. This approach improves sensitivity and dynamic range and offers other benefits. At the writing of this report, we learned from NASA that the Venus TLS (VTLS) has been selected as part of the DAVINCI Venus probe Discovery mission in which VTLS will measure key gases including all three isotopes of oxygen and sulfur to provide insight into the complex atmosphere-surface chemistry of Earth's sister planet. This VTLS instrument will be a 4-channel laser spectrometer, with MDL-developed lasers at 2.63, 2.78, 4.16 and 7.4 µm. The 4.16-µm channel will be used to look for phosphine PH_3.

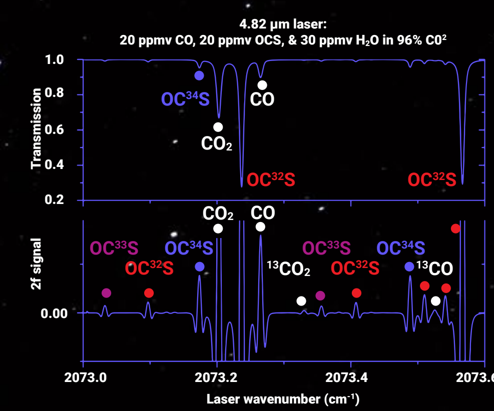
The laser technology integral to the performance of TLS was originally developed at MDL by teams led by Drs. Rui Yang and Siamak Forouhar. Dr. Chris Webster is the TLS instrument lead for both Mars TLS and Venus VTLS instruments. MDL's Drs. Ryan Briggs and Mathieu Fradet, as well as other JPL staff including Greg Flesch and Dr. Lance Christensen, were involved in the new developments for TLS.



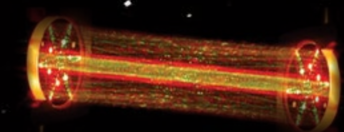
One of the TLS mirrors showing holes in the aluminum spherical mirror for four-channel injection.



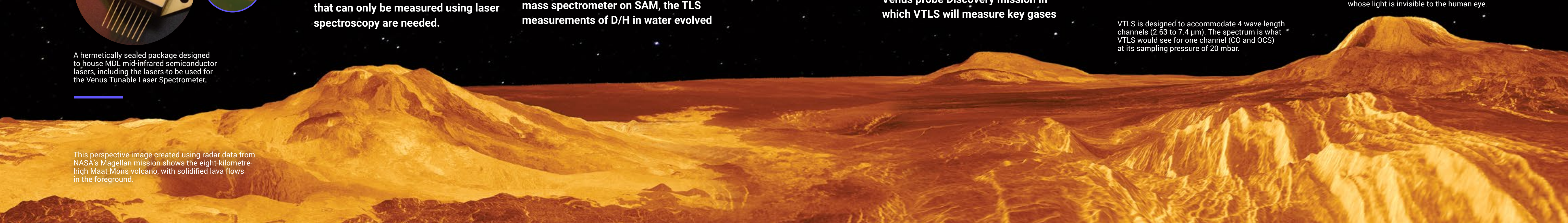
Visible laser demonstration of the orthogonal spot patterns for the two-channel TLS as operating on Mars. The cell detector records spectra only after the full multi-pass of either 43 or 81 passes.



VTLS is designed to accommodate 4 wave-length channels (2.63 to 7.4 µm). The spectrum is what VTLS would see for one channel (CO and OCS) at its sampling pressure of 20 mbar.



This schematic shows pieces of the TLS instrument, one of three instruments in the Sample Analysis at Mars instrument suite on NASA's Curiosity rover. As seen in the graphic above, the Tunable Laser Spectrometer has two infrared lasers whose light is invisible to the human eye.



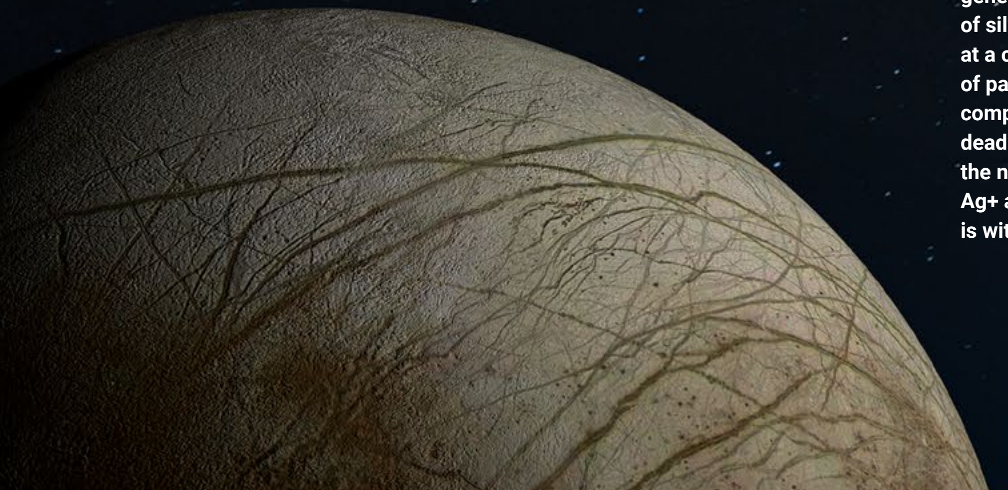
This perspective image created using radar data from NASA's Magellan mission shows the eight-kilometre-high Maat Mons volcano, with solidified lava flows in the foreground.

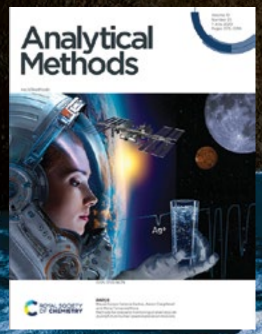
CHEMICAL ANALYSIS & LIFE DETECTION

FROM DETECTING LIFE TO SAVING LIFE

An analytical approach developed at MDL to detect life on ocean worlds like Europa and Enceladus has been repurposed to test recycled drinking water on human space exploration missions.

Future human space exploration and current occupation of the International Space Station (ISS) require that primary necessity for life, water. Technologies pioneered on ISS will be developed further for future space exploration to the Moon and Mars and include the process of recycling water. Multiple stages of cleansing of the water remove both inorganic and organic potential impurities, each of which may inadvertently introduce other inorganic or microbiological contaminants. Microbial analysis in a spacecraft is not feasible and consequently, a biocide is added to the water. One approach NASA is considering for its next generation technologies is the use of silver ion (Ag+) as the biocide at a concentration a few hundreds of parts per billion (ppb), which is completely safe for humans but deadly for microbes. This has led to the need for sensitive and accurate Ag+ analysis to ensure that its level is within the required limits.





THIS COVER CONCEPT SUMMARIZES THE METHOD AND ITS POTENTIAL FOR FUTURE HUMAN SPACEFLIGHT

The cover of the journal Analytical Methods, July 2020.

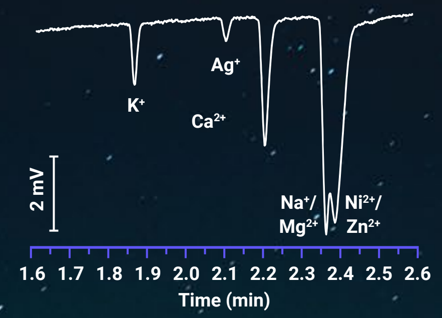
LAYING THE FOUNDATION FOR THE NEXT GENERATION OF LIFE DETECTION INSTRUMENTS

For the last 15 years MDL has continued to develop life detection approaches for flight missions as a result of grants from NASA as well as JPL funding. Although these technologies have many potential applications, currently the targets of greatest interest are the ocean worlds, like Europa and Enceladus. In particular, capillary electrophoresis has emerged as a powerful and versatile analytical tool, for analysis of both organic and inorganic analytes. This technique can be coupled to multiple detection systems, including fluorescence detection for sensitive analysis of amino acids. A prototype of such an instrument was validated in the Atacama desert in Chile in 2019. The instrument was mounted on top of a rover and operated remotely, without user intervention, for analysis of soil samples.

This type of detection was the focus of the work at MDL for many years but now we are expanding this technology to other detection systems. When coupling capillary electrophoresis to a contactless conductivity detector it is possible to detect also inorganic species, such as silver ions. With smart lateral thinking, MDL scientists realized that this technique could provide a potential solution to monitoring silver ions in the water aboard the ISS. With support from the NASA Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program it was possible to refine the approach, undertake experiments to test its applicability and check if it could do this particular job.

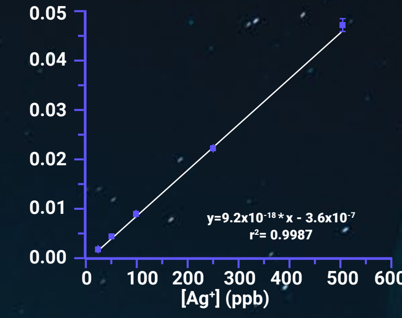
The results of the tests were outstanding. The system showed a linear measurement response throughout its range from the very sensitive lower limit of 30 ppb up to 500 ppb, with no interference from other ions present in the solutions. There was an added bonus also: with small changes to the operating procedure it was possible to measure the concentrations of other ions of interest present in the water. The work was published in the prestigious journal, Analytical Methods, as an invited contribution to the "Emerging Investigator Series". It also gained the honor of being publicized on the front cover.

The MDL team is also expanding the applications of our technology to human spaceflight. Drs. Mora, Noell and Ferreira Santos recently developed a method to monitor silver ions in the recycled water of the ISS. This work was part of the postdoctoral experience of Dr. Ferreira Santos, whom now has been converted to a full-time JPL employee.



Electropherogram of the separation of the standard mixture at 100 parts per billion with 0.5 M acetic acid as the background electrolyte.

Figures © The Royal Society of Chemistry 2020



Calibration curve for Ag+ ranging from 25 to 500 parts per billion (0.23–4.6 μM). Background electrolyte: 0.5 M acetic acid. Each point represents the average of triplicate measurements, and the error bars represent standard deviation.

A closeup of the liquid handling stage on the Chemical Laptop.

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

ENVIRONMENTAL AWARENESS

For any of these actions to succeed it is essential to understand the extent of the present problem and how successful mitigation is. To this end, MDL produces the vital sensors and sensing systems that must be used to make large-scale quantitative assessments of the concentrations of greenhouse gases.

THERE IS AN URGENT NEED FOR A WIDE RANGE OF ACTIONS TO ACCELERATE METHANE (CH_4) AND CARBON DIOXIDE (CO_2) MITIGATION, CLIMATE ADAPTATION AND CONSERVATION

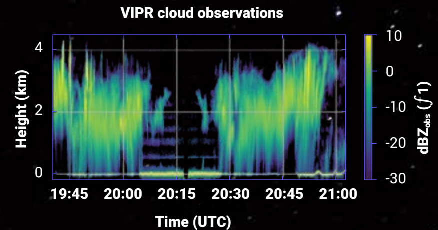
VAPOR IN-CLOUD PROFILING RADAR

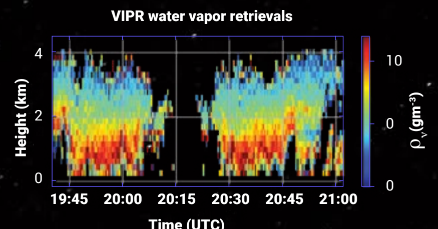
MEASURING HUMIDITY ON EARTH AND MARS

A new method for using radar to measure the amount of water in the atmospheres of both Earth and Mars is achieved using MDL-fabricated Schottky diode components.

WATER VAPOR IS A MAJOR SOURCE OF UNCERTAINTY IN ATMOSPHERIC MODELING, AND CURRENT REMOTE SENSING INSTRUMENTATION STRUGGLES TO PROVIDE CRITICAL HIGH-RESOLUTION WATER VAPOR PROFILES INSIDE OF CLOUDS.

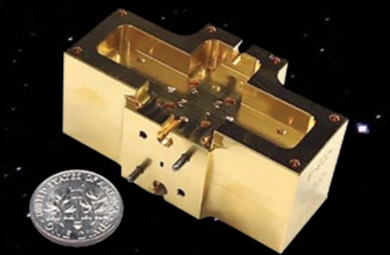
A NEW RADAR-BASED APPROACH TO HUMIDITY PROFILING INSIDE OF CLOUDS IS BEING PIONEERED AT JPL.



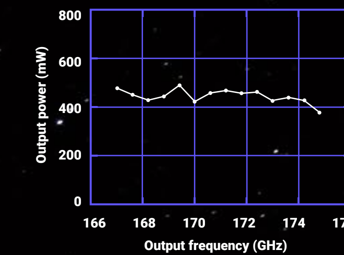


A simulated 3D view of recurring slope lineae on Mars (Hale Crater). The imaging and topographical information come from the High Resolution Imaging Science Experiment.

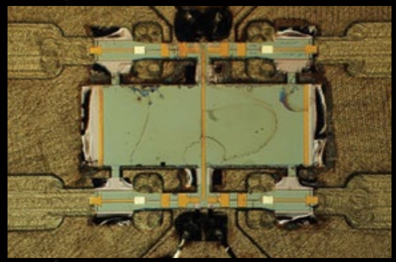
MDL-FABRICATED DEVICES ENABLE FIRST EVER DIFFERENTIAL ABSORPTION RADAR MEASUREMENTS



VIPR's RF source 170 GHz Schottky diode frequency-doubler.

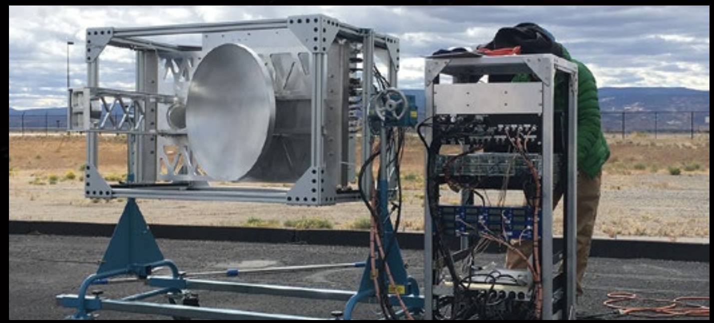


World record power for a solid-state source.



MDL-fabricated Schottky diode.

Members of the VIPR development team preparing to fly with the radar in a Twin Otter aircraft.



Airborne-ready VIPR in ground testing.

Measuring the amount of water vapor in the atmosphere is important for weather forecasting and climate modeling. For example, water vapor drives cloud formation, which can either shield Earth's surface from the Sun or enhance the greenhouse effect. To better understand cloud thermodynamics, high-resolution measurements of the distribution of water vapor are required. Vapor In-Cloud Profiling Radar (VIPR) is the world's first approach to measure humidity inside clouds using the technique of differential absorption radar. The radar beam's frequency is matched to a high-frequency resonance at which water vapor absorbs radiation. Monitoring the radar beam's reflection from cloud particles as the radar frequency changes gives a quantitative estimate of the amount of water vapor inside a cloud. VIPR was first tested and validated in ground-based experiments, followed by an airborne deployment to survey clouds from above.

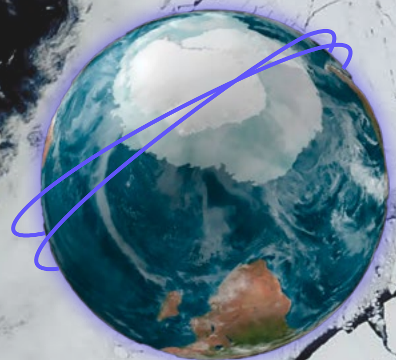
One major technical challenge to the successful implementation of VIPR's approach was to produce a sufficiently high-power radar beam operating near the water vapor resonance at 170 GHz. MDL engineer Dr. Choonsup Lee fabricated the critical gallium arsenide Schottky diode frequency doubler devices that are the heart of VIPR's transmitter. The frequency doublers generate over 300 milliwatts of power, allowing for sensitive radar measurements to be made even at ranges of several kilometers.

This development has been supported by the NASA Earth Science Division's Instrument Incubator Program (IIP). However, the world is not enough! A recent award from the NASA Science Mission Directorate (SMD) in the Maturation of Instruments for Solar System Exploration (MatISSE) is supporting the development of Water-vapor Sounding Short-range Radar (WASSR), a prototype instrument demonstration to show how local atmospheric humidity over the Martian surface can be measured from an *in situ* platform. Understanding the present Martian climate is part of the effort needed to resolve why Mars lost its atmosphere and water. For the dry, very thin Martian atmosphere, an even higher-frequency radar signal is needed, so WASSR will utilize an MDL-fabricated 557 GHz signal source, about three times the frequency needed for VIPR.

THERMOPILE DETECTORS

THE ARCTIC IS EARTH'S THERMOSTAT

MDL DETECTORS CAPABLE OF ACHIEVING HIGH RESOLUTIONS IN RECONFIGURABLE CHANNELS COULD BE UTILIZED TO QUANTIFY AND TRACK ATMOSPHERIC TRACE GASES



Two spacecraft in polar orbits sample Arctic and Antarctic surfaces and clouds, providing sub-diurnal coverage.

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

For PREFIRE, two CubeSats placed in a low-altitude polar orbit are expected to launch in 2023.

THE HIGHEST-DENSITY THERMOPILE ARRAY (64 X 8) EVER FABRICATED AT MDL IS PART OF THE PREFIRE FOCAL PLANE ASSEMBLY

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 that will make radiometric measurements of the atmosphere. One key to improving predictions of climate change is an understanding of the Arctic longwave spectral balance, which shifts with the seasons at wavelengths longer than traditional Earth sensors have measured. To access these wavelengths, PREFIRE will use a JPL-designed instrument that uses critical technology from MDL, crucially implementing 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, as well as related changes in cloud cover and the surface conditions below. The two PREFIRE CubeSats will make radiometric measurements of the atmosphere between 5 to 50 micrometers, fully characterizing the variability in FIR emission on scales of hours to months. This spectral data will provide 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.

After the PREFIRE measurements provide this unique new view of the planet's coldest areas, we foresee integrating the MDL thermopile detectors into a smart instrument capable of achieving higher resolutions in re-configurable channels that could be utilized to quantify and track atmospheric trace gases, as well as to characterize cloud thermodynamic phases and ice properties such as optical thickness and effective radius. This Pathfinder Observations of Spectral and Temporal Far-Infrared Radiant Energy (POSTFIRE) concept produces an instrument capable of R = 512 with contiguous spatial scenes for imaging across the cross-track swath.

The PREFIRE and POSTFIRE focal plane arrays operate uncooled, so minimal resources are needed to integrate the array into a spacecraft, keeping the payload light and low cost. Each pixel of the thermopile detector arrays has a broadband optical coating called "gold black" that provides near-unity optical efficiency across the entire spectrum that PREFIRE will measure. The arrays utilize custom readout integrated circuits built by Black Forest Engineering that show no measurable low-frequency noise. Therefore, the entire array can observe the Earth over long integration times to enhance the signal-to noise ratio of the measurement. A key development to enable POSTFIRE is close-packed arrays that achieve contiguous imaging.

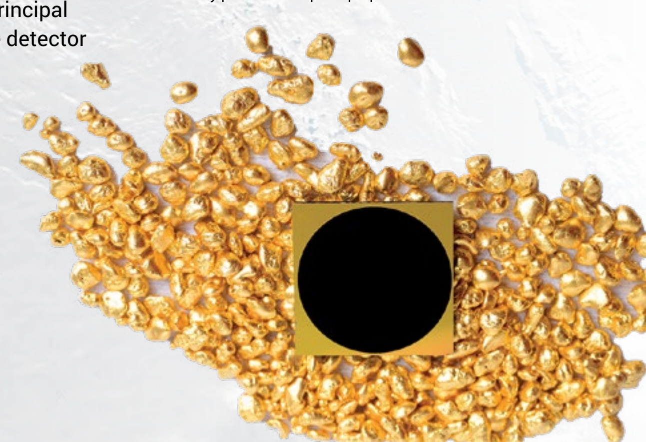
The principal investigator for PREFIRE and POSTFIRE is Dr. Tristan L'Ecuyer, associate professor of atmospheric and oceanic sciences at the University of Wisconsin–Madison. The principal investigator for the thermopile detector is Dr. Matt Kenyon at MDL.

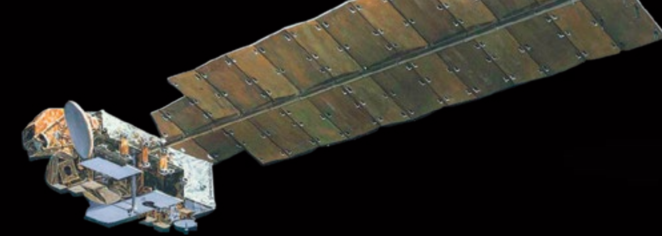
The back of the detector chip, which gives a sense of how we have carved out most of the silicon. This chip is the enabling technology of PREFIRE.

ONE PERCENT OF GLOBAL PERMAFROST METHANE HAS THE SAME ENVIRONMENTAL IMPACT AS 99 PERCENT OF GLOBAL ATMOSPHERIC CARBON DIOXIDE

The flight 64 x 8 element thermopile array, which has a new 'diamond' bulk micromachined design to remove most of the silicon from the substrate to reduce the electrical capacitance to ground. This reduction lowers the noise by 30-50%.

"Gold black" is made by evaporating gold in a nitrogen atmosphere, resulting in a film that has nearly perfect absorption properties.





SUBMILLIMETER DEVICES

PREDICTIONS OF CLIMATE CHANGE

Measuring many chemical species involved in the destruction of stratospheric ozone.

The stratosphere plays many important roles in Earth's systems. Spaceborne observations of its composition and temperature, particularly those from NASA's Microwave Limb Sounder (MLS) instruments, have proven essential to quantifying the depletion and initial recovery of stratospheric ozone, the contribution of stratospheric water vapor to as much as 30% of equilibrium climate sensitivity (the response of surface temperature to changes in CO_2), and the role of stratospheric circulation changes in driving 50% of the variability in ozone in the troposphere, where ozone is a pollutant and a greenhouse gas. The 15-year stratospheric ozone profile record from MLS on Aura (launched in 2004) is considered the "platinum standard" by the research community, and its other products continue to be heavily used in research worldwide, with over 1,300 peer-reviewed publications to date. The need to further such observations has been emphasized in the recent Earth Science Decadal Survey and other community roadmaps.

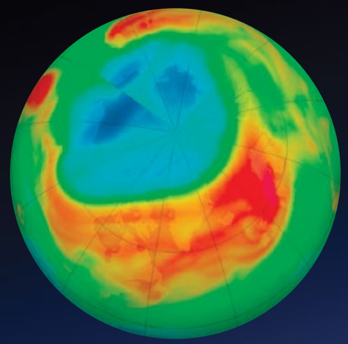
Despite the success of the Montreal Protocol, which was implemented to protect the ozone layer, there are still threats to the ozone layer, and every additional year of MLS observations reveals new information about the trends in and variability of stratospheric composition. These data provide both important checks on our understanding of climate and improved quantification of feedback mechanisms. However, given the ever-growing list of critical Earth system parameters that can be observed from space, there is a clear need for a lower-cost means of continuing the MLS record. Thanks to dramatic technological advances in microwave technology in the last two decades, it is now possible to build an instrument, Continuity MLS (C-MLS), that can continue the unique MLS observational record in a far smaller package(e.g., 50 kg, 50 W compared to 500 kg, 500 W for Aura MLS).

EXTENDING THE 15+-YEAR RECORD OF AURA MLS.

Improvements in both active and passive devices have contributed to this dramatic reduction in mass and power requirements. This advancement continues the extensive history of development of one of MDL's core areas of expertise, supported by the NASA Research Opportunities in Space and Earth Sciences (ROSES) system with successive awards from programs such as the American Rescue Plan Act (APRA), Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO), Maturation of Instruments for Solar System Exploration (MatISSE), Advanced Component Technologies (ACT), the Instrument Incubator Program (IIP), and others.

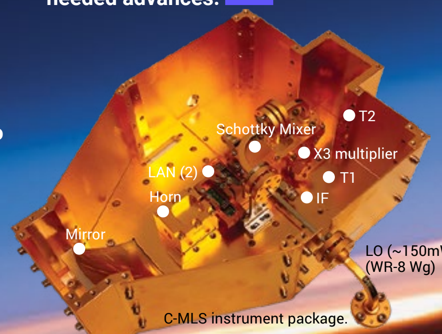
The main components of these instruments are gallium arsenide (GaAs)-based Schottky diode devices for the primary sensors. Most recently, there have been considerable improvements in the sensitivity and reliability of these active devices fabricated at MDL. Furthermore, a passive device developed and fabricated at MDL is the microelectromechanical system (MEMS)-based waveguide switch to be used for the C-MLS instrument's calibration scheme. This is the first time an integrated calibration system is being used for submillimeter-wave spectrometers.

The devices used in the C-MLS instrument were developed at JPL and elsewhere, but those fabricated at MDL are key to these much-needed advances.



Arctic stratospheric ozone reached a record low level of 205 Dobson units on March 12, 2020.

An image taken by astronauts aboard the International Space Station (ISS). The image presents an edge-on, or limb view, of the Earth's atmosphere as seen from orbit.



C-MLS instrument package.

Illustration depicting the HyTI CubeSat in low Earth orbit.

METASURFACE LWIR DETECTOR ARRAYS

TAKING EARTH'S TEMPERATURE

A technology to enable the next generation of infrared remote sensing.

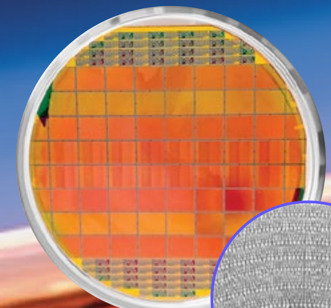
The infrared part of the electromagnetic spectrum contains information that allows researchers to extract scientifically interesting data, for example, water vapor content in the atmosphere and land and sea surface temperatures. Such knowledge has direct implications for weather forecasting and our ability to monitor the effects of a changing climate. Some of these effects, such as forest fires, present immediate dangers, whereas others, such as droughts, can occur over a much more extended period. Spaceborne instruments provide a unique vantage point for early-warning systems and support the acquisition of long-term, large-scale statistics and trends to understand Earth's natural systems. The long-wave infrared (LWIR, 8-15 microns) and the mid-wave infrared (MWIR, 3-8 microns) are particularly interesting because the Earth's atmosphere is transparent in large parts of these wavelength ranges, or so-called atmospheric windows. These windows allow researchers to use satellites in the continuous, high-resolution study of very large areas of Earth. However, infrared detectors for such instruments need to be cooled to very low temperatures, often around 40 K, to reduce the thermal noise in the detectors. The cooling hardware required to reach these temperatures adds significantly to the size, weight and power consumption of these instruments and prevents them from being used for small satellite missions. The deployment of infrared imaging technologies in such satellite missions would enable a relatively low-cost platform for future Earth-monitoring systems. For example, constellations of small satellites could be on the lookout for forest fires, surface deformation, mass movements, soil moisture, vegetation, topography, pollution, and water resources.

MDL is developing barrier infrared detector (BIRD) technology for infrared detectors together with digital readout integrated circuits (DROICs), as well as light-collecting optical concentrators to increase the signal-to-noise ratio. BIRD is a breakthrough technology that utilizes bandgap engineered III-V semiconductor heterostructures to create a continuously adjustable detector cutoff wavelength while simultaneously delivering a high signal-to-noise ratio. Metasurfaces—nanostructured surfaces—can be used to create planar, lightweight and versatile alternatives to conventional optical components.

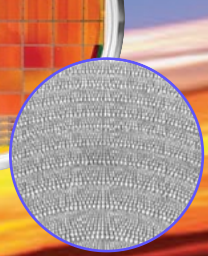
MDL is leveraging this approach to create optical concentrators and filters that can be monolithically integrated with BIRDs and enhance the light-collection of individual focal plane array (FPA) pixels. These complementary developments can allow detectors to function at higher temperatures and therefore require less cooling hardware than do current infrared detector technologies. This technology can enable infrared instruments in small satellite missions, as well as larger Earth-observing satellites in the future.

A high-operating temperature (HOT) BIRD FPA is currently being developed at MDL for the Hyperspectral Thermal Imager (HyTI) mission. HyTI is a CubeSat project that will demonstrate infrared imaging technology in a highly compact form factor. The launch of HyTI under the NASA CubeSat Launch Initiative program is the first opportunity to demonstrate BIRD technology in space and will enable next-generation LWIR image acquisition technology. These infrared detector developments at MDL are funded by NASA's Earth Science Technology Office (ESTO), defense and intelligence programs, and by JPL internal investments.

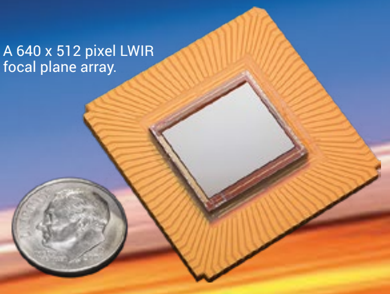
HyTI is a joint project led by the Hawaii Space Flight Laboratory (principal investigator Dr. Robert Wright, along with collaborators Paul Lucey, Luke Flynn, and Dr. Miguel Nunes), SaraniaSat, Inc. (Dr. Tom George), and JPL. JPL scientists, including Drs. Sarath Gunapala, Sir (Don) Rafol, David Ting, Alexander Soibel, Brian Pepper, Sam Keo, Arezou Khoshkhlagh, Cory Hill, and Tobias Wenger, are utilizing BIRD technology along with light-trapping metasurface lenses and DROICs to increase the signal-to-noise ratio. The performance increases could enable infrared detectors to operate at higher temperatures, but with the same (or better) sensitivity.



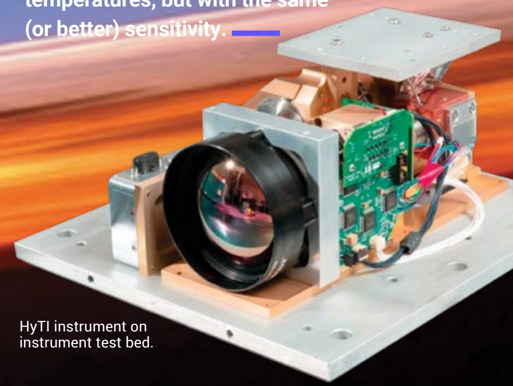
Metasurface LWIR detector arrays fabricated on a 4-inch GaSb substrate using stepper lithography.



Scanning electron microscope image of a gallium antimonide (GaSb) metalens fabricated using e-beam lithography and chlorine and fluorine plasma etching to define the nanopillars. These metalenses are fabricated on the back side of the focal plane array, and they have been shown to decrease dark current, thereby increasing the operating temperature by 25 K.



A 640 x 512 pixel LWIR focal plane array.

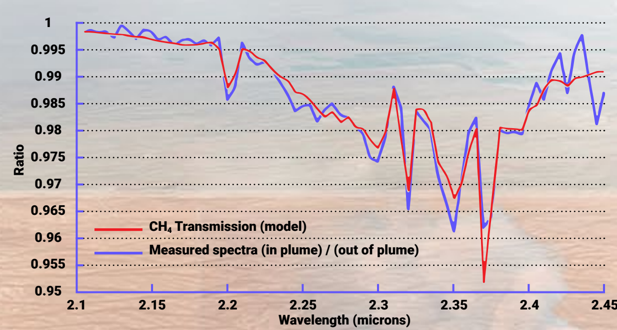


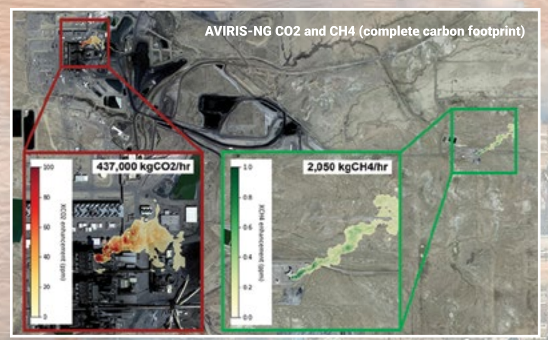
HyTI instrument on instrument test bed.

JPL IMAGING SPECTROMETER

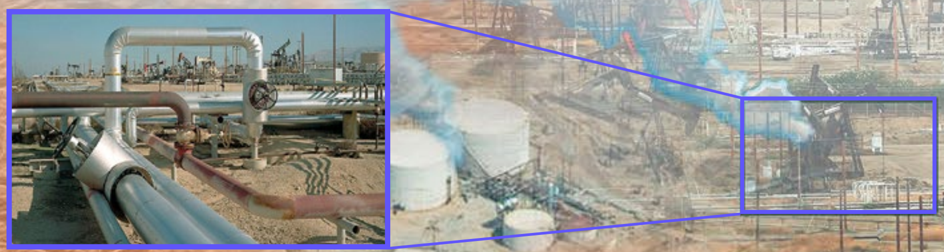
CARBON PLUME MAPPER FOR OUR FUTURE

A new initiative involves adding satellites to existing aircraft monitoring strategies to identify point-source and localized greenhouse gas emissions and expand mitigation efforts globally. The JPL-developed Carbon Plume Mapper imaging spectrometer will deliver high spatial resolution in combination with exceptional spectral sensitivity to directly map methane and carbon dioxide plumes from space. The breakthrough performance of this JPL-designed imaging spectrometer is enabled by state-of-the-art MDL grating, slit, and stray light trap components.





Satellite constellation to map greenhouse gases and identify super-emitters.



An innovative consortium is being assembled by Carbon Mapper, Inc., a California nonprofit, with a mission to help mitigate human impacts on Earth's climate and ecosystems. The Carbon Mapper project is a public-private partnership that will develop new capabilities to identify and track local greenhouse gas emissions, which come from oil/gas infrastructure, power plants, landfills, agricultural sources, and more. Every greenhouse gas has a Global Warming Potential (GWP), which is calculated based on how long the gas stays in the atmosphere and how strongly it causes warming. Over a 20-year period, methane has about 85 times the GWP of carbon dioxide. While methane is a key focus, Carbon Mapper is also tackling fuel CO_2 emissions. Using the broad spectral range of the JPL imaging spectrometer, Carbon Mapper will deliver new ecosystem health and diversity products, as well.

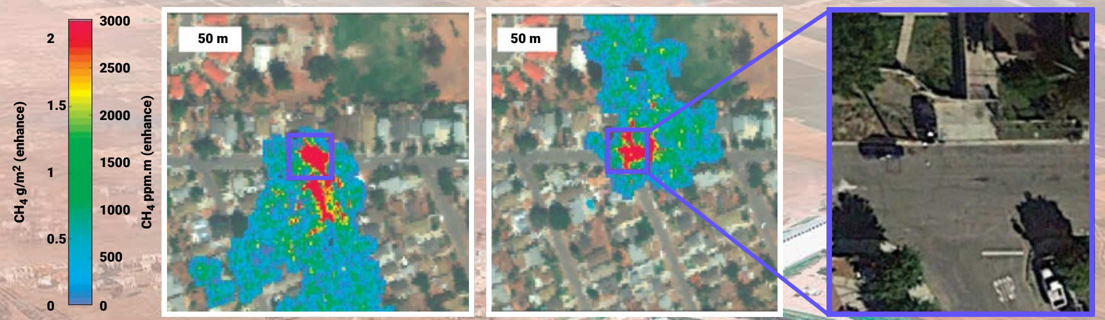
For the last few years, Carbon Mapper and its precursor efforts have been using aircraft carrying JPL-developed imaging spectrometers to look at methane emissions across the US. However, to take this capability global requires satellite observations. Making these measurements from space is challenging, but they can be achieved by using optimized MDL device components in conjunction with a high-throughput imaging spectrometer design. JPL has a decades-long history of advancing imaging spectrometer design and development for NASA and other customers. Current developments include the Mapping Imaging Spectrometer for Europa (MISE), Earth Surface Mineral Dust Source Investigation (EMIT), and the High-Resolution Volatiles Minerals Moon Mapper (HVM3). At the heart of each of these instruments are unique and finely optimized components developed at MDL. The gratings, slits, and stray light traps are the result of more than a decade of MDL development and refinement, as well as use and testing in previous imaging spectrometers such as Hyperion, CRISM, M3, AVIRIS, and others.

Carbon Mapper plans to launch two demonstration satellites with JPL-designed and MDL-enabled Carbon Plume Mapper (CPM) imaging spectrometers in 2023, and it intends to expand dramatically to a fully operational constellation of many satellites by 2025. Its strategy is to bring together a broad set of entities with complementary skills and expertise.

JPL IMAGING SPECTROMETER ENABLED BY MDL DEVICES

In addition to JPL, Carbon Mapper's intended partners include the State of California Air Resources Board; Planet, a company that images Earth from space; the University of Arizona; Arizona State University; and RMI, a non-partisan, nonprofit organization working to transform global energy systems.

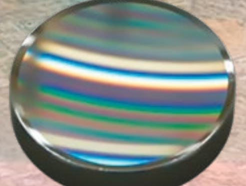
The CPM is a JPL imaging spectrometer being developed for the Carbon Mapper consortium (https://carbonmapper.org). The state-of-the-art CPM instrument will measure methane and carbon dioxide plumes from space with unprecedented combined spatial resolution and spectral precision. Its high spatial resolution enables the direct observation of plumes, which can be used to directly support greenhouse gas source mitigation. The CPM instrument is being developed at JPL and is enabled by MDL efficiency tuned diffraction gratings, ultra uniform slits, and custom black silicon light traps. The CPM builds on two decades of JPL investments in high-fidelity imaging spectrometers.



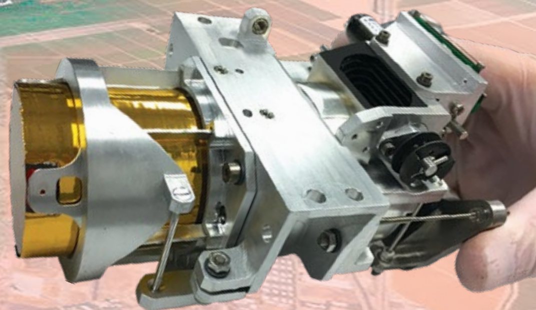
Mitigation of neighborhood natural gas leak using airborne measurements.

Light trap

Slit



Grating



Prototype spectrometer

TRAILBLAZERS

PAULA GRUNTHANER, 1974

Concurrent with her undergraduate studies at Caltech, Paula Grunthaner joined JPL in 1974 as an academic part-time employee responsible for implementation of the laboratory's new state-of-the-art X-ray photoemission spectrometer including experimental design, sample preparation, and data interpretation for semiconductor interface research central to radiation effects on electronic devices.

MDL RECOGNIZES THE SUCCESS OF WOMEN AT NASA JPL WHO ARE WORKING IN THE FIELDS OF SPACE SCIENCE, ENGINEERING AND TECHNOLOGY.

MDL SUPPORTS DIVERSITY, EQUITY, AND INCLUSION.

At MDL, we know that a supportive and inclusive workforce is also one that attracts and engages the brightest minds. By recognizing and utilizing our differences, we open the door to unexpected inspiration. Although MDL still has room for improvement, we are continuously striving to increase our recruitment of diverse staff. In that spirit of diversity, we celebrate the trailblazing women of MDL, whose varied backgrounds, experiences, and skills strengthen our performance and help keep MDL at the forefront of microdevice technology. The advice in the following pages, by 12 MDL women for women, aims to assist others with following their lead in helping MDL answer some of the biggest questions in the universe.

PAULA
GRUNTHANER

Dr. Gruntháner joined JPL in 1974 and retired in 2012. Her research focused on ultraviolet (UV)/visible and infrared (IR) sensors and *in situ* instruments. She led the startup of the silicon molecular beam epitaxy effort and received a NASA Engineering Award for the UV-sensitive delta-doped charge-coupled device (CCD). She later managed the Office of Advanced Planetary Instruments but returned to MDL to manage the *In Situ* Instruments Section and serve as the lead engineer for the Phoenix/MECA instrument. She worked on the Europa Flagship mission study before returning once again to Exploration Systems Development (ESD) to serve as the manager of the Mission Concept Section. She holds a BS and PhD in chemistry from Caltech.

What were some of your expectations coming to JPL?

I started working at JPL as an academic part-time employee while a sophomore at Caltech majoring in chemistry. My expectation was simply an interesting short-term job that would augment my Caltech education while providing a bit of extra spending money. But I soon came to realize that the opportunities at JPL were not only unlimited and inspiring but also open to anyone if you were willing to work hard and learn on the job. The next four decades were pure pleasure, as I worked well beyond my chemistry background on such diverse opportunities as applied research for future missions, programmatic interfacing with NASA for advanced planetary instruments, implementation of a flight instrument now on Mars, interfacing with our strategic university partners, and participating in and supporting mission formulation. You are never trapped in a career box at JPL.

What do you wish the public knew about the people and work that go into each of NASA's projects?

A NASA project is typically a one-of-a-kind mission that must survive in exceptionally hostile environments without human intervention other than communication signals. This is a challenge that demands creativity, innovation, and large teams of people who come together to cooperatively solve complex problems likely never encountered before. For the people who work on these projects, it's a passion, not a job.

How important do you feel STEM education is for NASA?

NASA's mission is to "drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality and stewardship of Earth." NASA's success is inherently and intricately tied to melding innovative technological and fundamental science advancements to create complex space missions. STEM as an educational paradigm, integrates the disciplines of science, technology, engineering, and math to stimulate creative thinking. This multidisciplinary mindset is what powers large mission teams to solve seemingly impossible problems. A strong STEM education starting at a young age will also nurture the next generation of scientists, technologists, and engineers to be inspired to join NASA in pursuit of the unknown. Last but not least, STEM is crucial for the public's understanding and appreciation of the impact of NASA's mission on all of our lives.

DO NOT BE AFRAID TO EXIT YOUR COMFORT ZONE

What advice would you give young women who want to take the same career path as you?

Do not overthink the specific STEM classes you will need for your future career. Get exposure to as many different STEM subjects as possible because you will find problem solving benefits from an integrative grasp of the fundamentals of many STEM topics, including physics, biology, chemistry, math, and engineering. It is not a specific aptitude in a topic, but rather your critical thinking, creativity, teamwork, and interdisciplinary knowledge that will serve you. Be confident in knowing that you will learn on the job and continue to grow throughout your entire career.

Do not be afraid of not getting it right. Instead, ask questions of your colleagues and identify one or more mentors who can help you navigate the organization and develop a network of colleagues. Do not limit yourself to a woman mentor—the best way to end workplace bias is not to practice it yourself. I waited 20 years before I stepped out of the comfort of my lab coat in a research lab. I so enjoyed the next 2 decades that I wish I had stepped out at least a decade sooner.

Q/A.

BARBARA
WILSON

Dr. Wilson joined JPL in 1988 as a technical group supervisor in the Microdevices Section following 10 years in basic research and management at AT&T Bell Labs. In 1991 she became manager of MDL, and in 1999 was named JPL's Chief Technologist. Under an interagency loan, she also served as Chief Technologist for the Air Force Research Laboratory. Dr. Wilson is a Fellow of the American Physical Society and former APS Executive Board Member. She was elected to the International Academy of Astronautics in 2000. She has received two Exceptional Achievement Medals from NASA and the Decoration for Exceptional Civilian Service and the Meritorious Civilian Service Award Medal from the US Air Force. She holds a PhD in condensed matter physics.

What were some of your expectations coming to JPL?

When I arrived at JPL, I was excited about coming to work for an institution known both for great research and for applying it to exciting questions in space and Earth sciences. What I hadn't expected was how much of a team environment I would find at JPL. Perhaps that is a natural outcome for an organization that successfully manages large, complex projects that require close teamwork, but I happily found that it extended all the way to the research environment at MDL, where shared equipment and lab space led to a friendly camaraderie.

How important do you feel STEM education is for NASA?

Education in science, technology, engineering and mathematics (STEM) is a vital underpinning of NASA's success. In today's world, many avenues to economic success require significantly less investment in rigorous academic programs, and STEM careers are not typically viewed as the easy path to great riches. On the other hand, with STEM training, the opportunities to participate in overcoming technical challenges pursued by our societies are varied and plentiful. Human and robotic space exploration, as well as observations made from space inward towards our home planet and outward to the far reaches of the universe, rely extensively on employees trained in STEM. NASA missions are complex technical projects that require not only in-depth discipline knowledge but also integration across disciplines to design, model, build and operate space systems that address exciting questions facing humankind today and in the future.

REMEMBER, THE ONLY DEFINITION OF SUCCESS THAT TRULY MATTERS IS YOUR OWN

What do you wish the public knew about the people and work that go into each of NASA's projects?

I think the public often underestimates the complexity and unique challenges that underlie any space mission project where the environment can be hostile, there are no repair shops if things wear out or break, and there is little or no opportunity for do-overs. You can't afford to just design a system to meet the performance requirements and call it a day because any glitches during flight can be mission ending. A tremendous effort needs to be expended to anticipate all the ways things might go wrong and to build in resilience to survive even unforeseen problems. This resilience requires an intimate interplay between the hardware and software systems and exhaustive testing to push the integrated system to failure in order to understand the vulnerabilities while still on the ground, where design modifications are possible. For scientists and engineers, this leap from lab-based research to space projects represents a challenge in terms of embracing both greater system complexity and fault-tolerant design.

What advice would you give young women who want to take the same career path as you?

For the next generation of young women entering STEM careers, the barriers to success are (hopefully) lower than they were for my generation or for the women before us. On the other hand, remaining biases, such as gender-based expectations, can be more subtle and harder to recognize and therefore may be more insidious. Consequently, it remains important to be a self-starter, to nurture your self confidence by seeking out professional relationships that support your sense of self worth, to soak up knowledge from all sources and people around you, and to "put your head down and go for it", even when some may be telegraphing less-than-positive messages about your perceived abilities and/or likelihood of success. There's a lot to be said for being persistent (some might say stubborn), tied to your own value system, and focused on your own goals—that's where I've found true satisfaction. And remember, the only definition of success that truly matters is your own.

SHOULEH
NIKZAD

Dr. Nikzad is a JPL Fellow, Senior Research Scientist, Principal Engineer, and technical supervisor for the Advanced Detectors, Systems, and Nanoscience Group. She also holds visiting faculty and lecturer appointments at Caltech. Her research interests span materials, detectors, coatings, and systems—especially in ultraviolet—and their applications in planetary sciences, astrophysics, space weather, and medicine. Many of these technologies are baselined for suborbital, CubeSat, and flagship missions. She is a Fellow of the IEEE, National Academy of Inventors, American Physical Society (APS), and SPIE, and she has received numerous awards and recognitions, including JPL's Lew Allen Award. She holds both a PhD in applied physics, an MSEE from Caltech and a BSEE from the University of Southern California.

Q/A.

What do you wish the public knew about the people and work that go into each of NASA's projects?

The media image of scientists and engineers is still either the lone thinker making discoveries or a group of nerds who are clueless about other aspects of life. My wish is for the public to know the passion, dedication, and diversity of the personalities and backgrounds that make up the scientists, technologists, and engineers at NASA. The work is intense in solving unique problems, and at times it is all-consuming. It takes creative minds and dedicated hearts to accomplish the goals of NASA projects. Science requires creativity, and it's a lot closer to art in that respect than the public recognizes. I also would like the public to recognize the context of this creative work and these discoveries, which are accomplished with a relatively small portion of the national budget.

ROLE MODELS AND MENTORS ARE FANTASTIC …BUT CREATE YOUR OWN PATH

What do you think is the next big thing for NASA science?

There is a lot of focus on understanding and discovering habitable planets beyond our solar system. There are plans to deploy very large observatories to Earth orbit. I have no doubt that, as with any observatory, there will be unexpected discoveries. Being both a NASA center and a Division of Caltech, JPL has the opportunity to contribute to NASA's mission of exploration and discovery and make advances that affect life here on Earth, both from an Earth science perspective and in terms of repurposing and spinning off technology. I also hope that our MDL technologies will be key enabling factors for these future discoveries.

In your opinion, after seeing everything you've seen here, why should people care about the work at NASA?

The type of work done at NASA appeals to what's best in all of us. The curiosity and sense of wonder, plus the creativity and perseverance necessary to turn wonderment into discoveries, can be a beacon for all humanity.

What advice would you give young women who want to take the same career path as you?

Be yourself, work hard, and don't emulate anyone. Role models and mentors are fantastic and really important to have, but create your own path. There is no substitute for being good at what you do, so achieve that in your own way!

APRIL
JEWELL

Dr. Jewell is part of JPL's Advanced Detectors, Systems and Nanoscience Group. Her work focuses on post-fabrication processing and optimization techniques for silicon-based imagers to fine-tune a detector's response for project- or mission-specific applications. Her work combines materials science and process development. She uses molecular beam epitaxy (MBE) for surface bandstructure engineering and atomic layer deposition (ALD) for nanometer-scale coatings and filters. Dr. Jewell's surface science background allows her to develop MBE and ALD processes that are general enough to be applied to virtually any silicon-based imager. She is a recent recipient of SPIE's Rising Researcher Award and JPL's Charles Elachi Award for Early Career Achievement. She has a BS from George Washington University and a PhD from Tufts University.

What do you wish the public knew about the people and work that go into each of NASA's projects?

I hate the phrase "good enough for government work"! It implies that those of us working with taxpayer dollars don't really care about the end product. I would hope that people know that we are genuinely passionate about the work that we do. The enthusiasm of the Mars Landers/Rovers Entry, Descent, and Landing (EDL) Teams is obvious from the televised events and their exuberance at a successful outcome after years of work. I worked for one day on the Mars2020 project, helping with an administrative task for the Enhanced Engineering Camera (EECam); it was not enough to be an official team member, but I am still so proud of the images coming back. I feel the same sense of pride when I solve a problem in the lab or make a delivery on any of my other tasks.

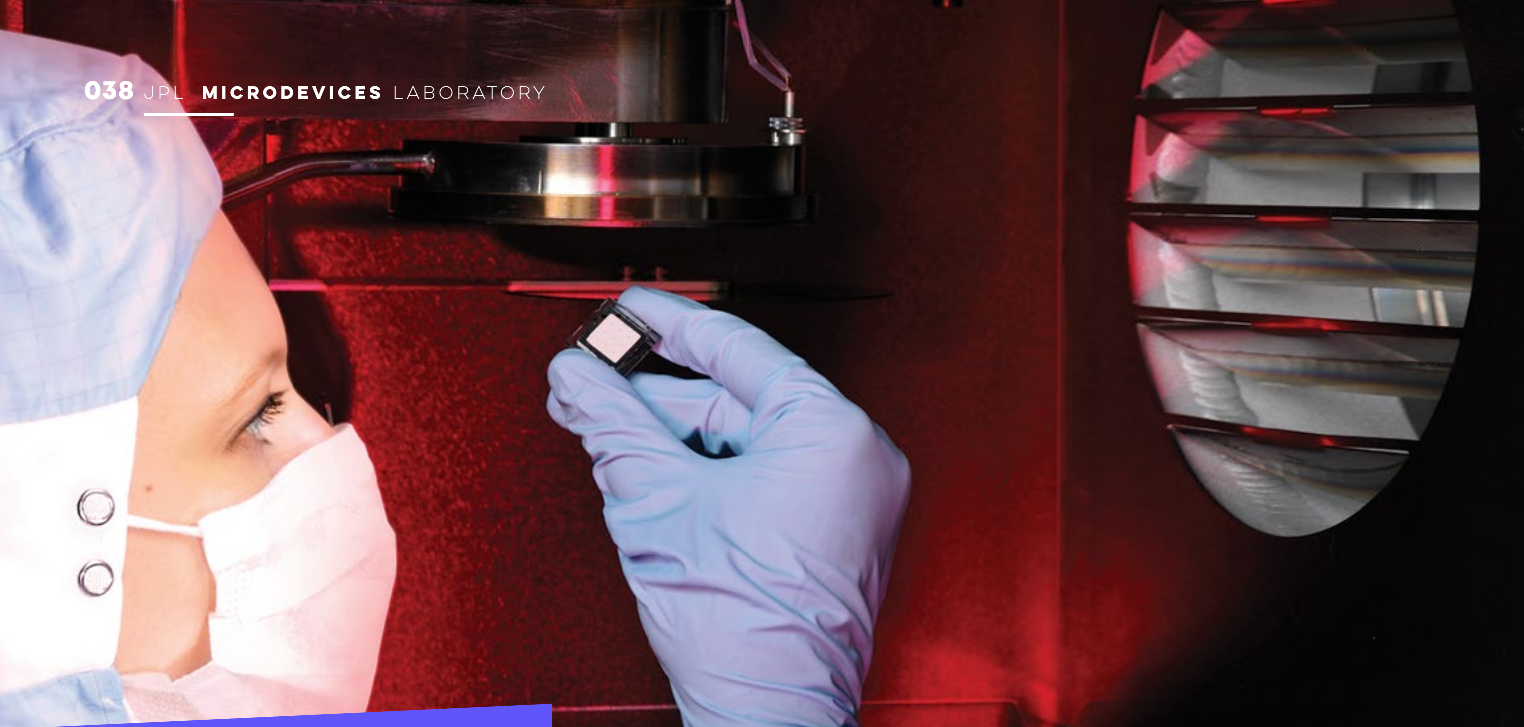
What advice would you give young women who want to take the same career path as you?

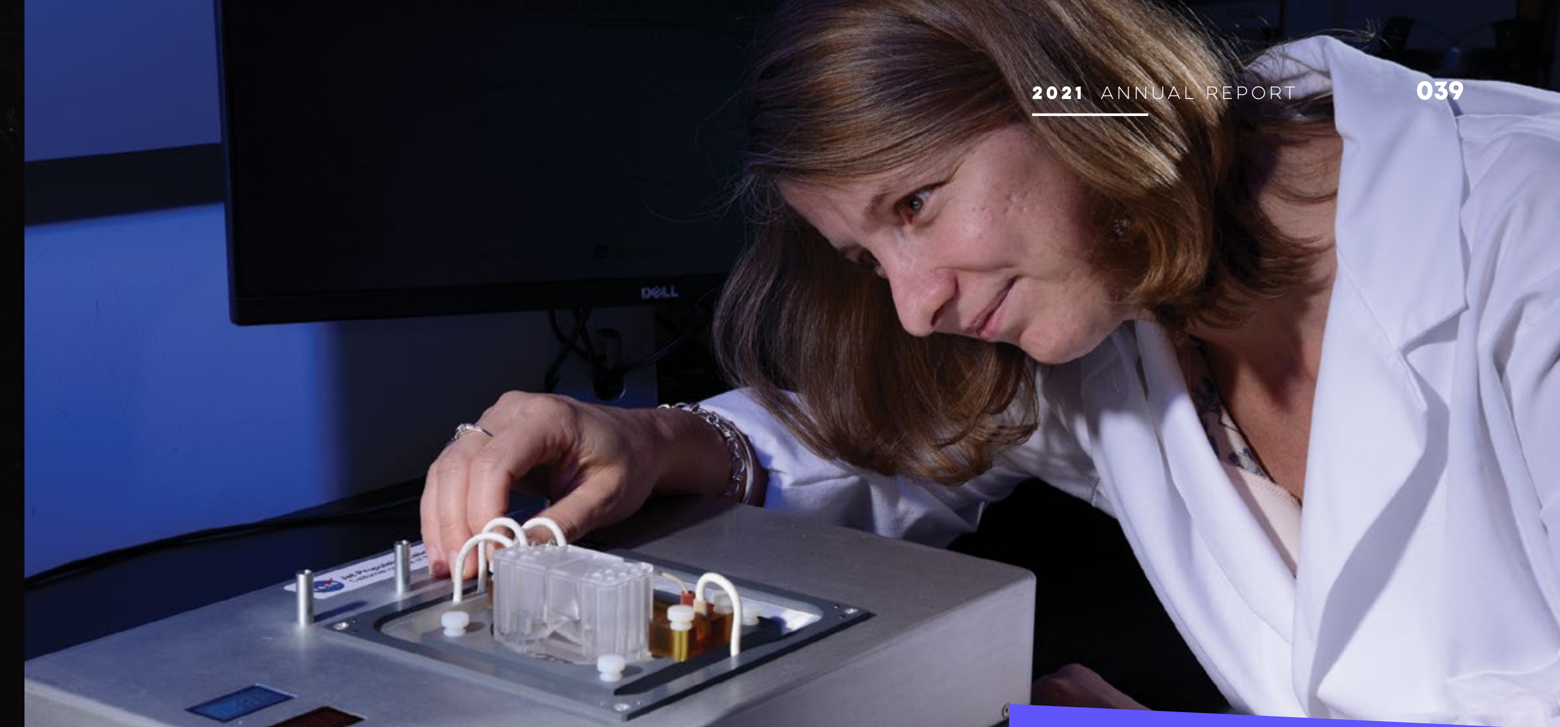
I would encourage young women not to self-limit when looking for job opportunities and to avoid the tendency to apply only for positions that exactly describe your background. Learning is a lifelong journey; it doesn't end when you get your degree, and there is nothing wrong with learning on the job. Also, get comfortable with the word "no." This is especially important in an environment like JPL, where proposal writing is the name of the game. Some common programs have a proposal selection rate of 10-20%, so "no" is something you will likely hear often. Again, learn what you can from the "no"s and use that information to make a better proposal (or job application, or anything else).

I WOULD ENCOURAGE YOUNG WOMEN NOT TO SELF-LIMIT

What were some of your expectations coming to JPL?

I started as a Summer Undergraduate Research Fellowship (SURF) student in Section 346 and fully expected my time at JPL to be confined to the 10-week program. I quickly fell in love with the Los Angeles area and the working environment at JPL. Toward the end of the SURF, my mentors brought up the possibility of future employment; I was a full-fledged JPLer six months later! I left the lab briefly to pursue a PhD on the east coast, but I couldn't stay away.





CECILE
JUNG-KUBIAK

Dr. Jung-Kubiak joined JPL as a NASA Postdoctoral Fellow and is now a member of the Submillimeter Wave Advanced Technology Group. Her research interests include the development of silicon micromachining technologies to build compact 3D instruments and the miniaturization of micropropulsion systems. She received the NASA Early Career Public Achievement Medal and the 2020 NASA Honor Award for early career achievements in the development of innovative silicon micromachining techniques that have enabled novel electromagnetic, mechanical, and propulsion devices.

Q/A.

THE JPL FAMILY IS VERY DIVERSE AND IT IS EXTREMELY ENRICHING

What do you wish the public knew about the people and work that go into each of NASA's projects?

There are a lot of people with different academic backgrounds working at JPL; not everyone is a rocket scientist or a master of robotics. Further, the JPL family is very diverse, and it is extremely enriching, both from a professional and personal standpoint, to be exposed to so many different cultures. While we have different backgrounds, we all have at least one thing in common: we are passionate about our work, and although long hours are frequent, we will give our best to ensure our projects are a success.

What advice would you give young women who want to take the same career path as you?

Be your worst critic but also your best supporter. You should keep challenging yourself so that you can learn every day, and do not be afraid to go the extra mile; it always pays off. Everyone makes mistakes, and you will too. Just learn from them and find solutions, think outside the box, so the next time, you succeed. Finally, numerous women working at JPL are also mothers. It takes a bit of juggling to have a successful career while having a family, but you can make it work!

How important do you feel STEM education is for NASA?

STEM education is essential for the future of space exploration, and we must spark interest at a young age. Special emphasis should be put into young females and underrepresented communities to keep attracting diverse students. Every successful project at JPL and NASA was built upon very diverse careers and upbringings.

What first attracted you to science or technology and at what age?

I've always been very curious about and observant of the world around me. I wanted to understand how things work. I remember a book called "How Things Work" that we had when I was 9 years old, and it fascinated me. I read it over and over; I didn't get tired of it. Also, my dad loved nature and the outdoors, and he always tried to teach us. I also remember a school field trip when I was probably also about 9; we went to a river to study different types of native plants. We had to observe the plants, takes notes describing them and the environment, and we collected leaves from each plant for our notebooks.

What advice would you give young women who want to take the same career path as you?

My advice is don't be afraid of trying new or difficult things and don't doubt yourself! Working hard is also a given, but beyond that, I think being willing to go outside your comfort zone is important. It's good to have a plan for what you want to do, but there might also be opportunities along the way that will take you on a new path. Don't be afraid of those opportunities, as they can be life changing!

How did you end up at JPL?

After I got my PhD, I stayed in the same lab for a few months while searching for postdoc opportunities. Every morning, the first thing I did was to check several websites where professors post ads looking for postdocs. One morning, I saw an ad about NASA postdoctoral fellowships. However, I thought it was probably only available to U.S. citizens, so I didn't even open the link. The next day, I saw the same ad as soon I got onto the computer, and then I became curious. I typed "microfluidics" in the search tab and I found an ad from Peter Willis looking for a postdoc with my exact experience. I couldn't believe it! That is how my JPL journey started.

What is your major achievement at JPL?

Probably receiving the Lew Allen Award. It was a big but very nice surprise! I've been at JPL for 10 years working on microfluidic instruments, and we have had ups and downs, so it felt very good to receive recognition from outside our group.

EVEN AS A CHILD, I GREATLY ENJOYED READING AND LEARNING NEW INFORMATION

FERNANDA
MORA

Dr. Mora began her time at JPL as a postdoc, where she focused on automating the microfluidic analysis of organics to enable implementation in spaceflight operational scenarios. She continued that work by developing the first portable, fully automated, reprogrammable, and battery-powered microchip electrophoresis instrument. Since then, her research has focused on developing new strategies for the analysis of inorganic and organic molecules via capillary electrophoresis (CE) and microchip electrophoresis (ME). She has extensive experience in the design, fabrication, and implementation of microfluidic devices coupled to optical and electrochemical detection techniques. Her current work involves developing strategies for the simultaneous analysis of inorganic ions and organic acids via ME and contactless conductivity detection, as well as analysis of organic biosignatures via CE and mass spectrometry. She received a bachelors in chemistry from the National University of Córdoba and a PhD from the University of Texas at San Antonio.

MINA RAIS-ZADEH

Dr. Rais-Zadeh leads microelectromechanical systems (MEMS) and micro-instrument development at JPL as a Group Supervisor for the Advanced Optical and Electromechanical Microsystems Group. In 2009, she joined the University of Michigan, Ann Arbor, as an Assistant Professor of Electrical Engineering and Computer Science (EECS). From 2014-2018, she was a tenured Associate Professor in EECS with a courtesy appointment in the Department of Mechanical Engineering. From 2008 to 2009, she was a Postdoctoral Research Fellow at the Georgia Institute of Technology. Dr. Rais-Zadeh received a BS degree in electrical engineering from Sharif University of Technology and MS and PhD degrees in electrical and computer engineering from the Georgia Institute of Technology in 2005 and 2008, respectively.

Q/A.

In your opinion, after seeing everything you've seen here, why should people care about the work at NASA?

Although NASA is generally viewed as an institution focused on space science and technologies, it conducts much work related to our own planet (Earth). The information NASA gathers through its various programs is crucial in understanding the path our planet is taking and in giving clues to help solve some of the problems we are experiencing, such as increased numbers of tropical storms and hurricanes, global warming, and increased rates of glacier melt. This information has a significant effect on our own lifestyle and that of future generations. NASA's planetary exploration and success (such as the Mars landings) show what humans are capable of doing when they put their minds to it.

STEM EDUCATION… NEEDS TO BE TAKEN VERY SERIOUSLY EARLY IN LIFE

How important do you feel STEM education is for NASA?

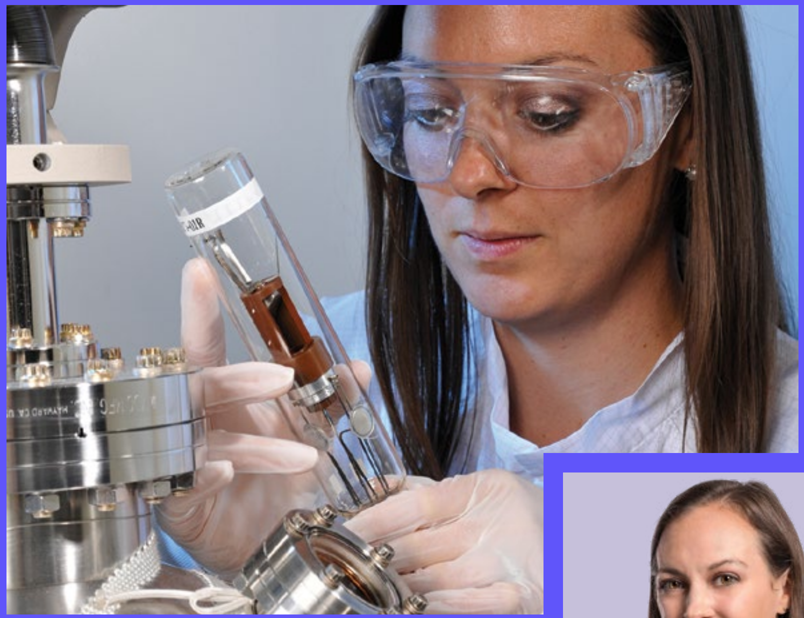
STEM education is very important and needs to be taken very seriously early in life to educate the next generation of engineers and scientists.

What do you think is the next big thing for NASA science?

Finding solutions for slowing global warming—Earth sciences—and finding signs of life on other planets—planetary science.

What do you wish the public knew about the people and work that go into each of NASA's projects?

The JPLers I have worked with are all very passionate about their work, and they go above and beyond the call of duty to deliver on their projects. They are true engineers and scientists who are working hard to solve some of the most important engineering and scientific challenges of our time.



VALERIE SCOTT

Dr. Scott is an engineer at JPL's MDL. She has multiple publications and patents and has received several JPL awards. She currently works with JPL's Commercial Program Office as a Chevron Technical Fellow. She has also supported Solar System Mission Formulation, served as Strategic Editor for a 2019 Discovery Mission proposal, and served as Strategic Editor and Lead Author for the payload sections of two JPL-led mission concept studies. She has led targeted studies for mission concept support through JPL's Planetary Science Directorate, has an upcoming KISS workshop funded, and is an A-Team Core Member. She works with partners to develop highly miniaturized payloads and has contributed to several technology developments, from harsh environment components to a "tactile" wheel. Currently, she is developing a combination Mössbauer/X-ray fluorescence spectrometer and a laser ablation-mass spectrometer for dating geological samples. She holds bachelor's degrees from Brandeis, a master's from Purdue, and a PhD from Caltech.

How important do you feel STEM education is for NASA?

The importance of STEM education can't be overstated. Getting kids comfortable with STEM while also giving them an appreciation of how much we still don't know is key to getting them on STEM paths. STEM education also helps those who don't end up on STEM paths understand broadly what NASA is doing and enables them to enjoy what their country is doing. It's worth noting that literature, art, and history impact STEM fields similarly and often directly impact the creativity seen in mission concepts.

What were some of your expectations coming to JPL?

Coming to JPL was an unusual move for me given my organometallic chemistry background. I was quite afraid I'd miss the nitty-gritty of reaction chemistry. Instead, I was pleasantly surprised to find very interesting and unexpected applications of my skill set in an environment of never-ending learning.

What advice would you give young women who want to take the same career path as you?

If you love it, go for it. Talk to people and be confident in what you bring to the table. Also, try not to be so narrowly focused on a goal that you accidentally close yourself off to opportunities.

What solar system destination are you still most excited/eager for NASA to still go explore?

I think the thing that is the most exciting to me is a return to Venus, and in particular, doing an *in situ* mission. The past similarities to Earth (and present differences) make it really intriguing. Given the incredibly harsh environment, figuring out a way to survive on and learn about the surface would be an incredible engineering feat.

In your opinion, after seeing everything you've seen here, why should people care about the work at NASA?

NASA embodies science and engineering being pushed to the limits, which is really fun to witness and directly impacts us, whether we know it or not. Many NASA-engineered technologies make it into everyday life.

IF YOU LOVE IT, GO FOR IT

SOFIA RAHIMINEJAD

Dr. Rahiminejad is currently working in the Advanced Optical and Electromechanical Microsystems Group at MDL. Her interests lie in the fields of innovation and microsystems. She co-invented three patents, has published over 20 papers, and was a recipient of JPL's Postdoc Research Day Award in 2019. In 2011, she received her MSc double diploma from the Katholieke Universiteit Leuven, Belgium, and Chalmers University of Technology, Sweden, in nanoscience and nanotechnology as a part of the Erasmus Mundus masters program. In 2016, she was awarded her PhD in micro and nanotechnologies for integrated systems from Chalmers University of Technology.

■ What were some of your expectations coming to JPL?

I didn't know what to expect and didn't know a lot about space, but I was very excited to work with the people here. I knew that the people at JPL were very knowledgeable about high frequency technologies, micromachining and advanced microelectromechanical systems (MEMS) components, and I wanted to learn from these experts.

■ What solar system destination are you still most excited/eager for NASA to still go explore?

Ocean worlds because there is something very exciting about bodies that have so much potential. There is so much to explore, and the things we can learn are very exciting.

■ What advice would you give young women who want to take the same career path as you?

Do what you think is interesting and fun, and then all the hard work will be worth it. Don't care about what other people think you should do; trust your gut. Be open to opportunities, and don't think "I can't do that"; instead, try and see, and know it's okay to fail. Also, if you can, travel and meet different people; it will be to your benefit later in life.

EVERYBODY PLAYS A PART IN MISSION SUCCESS

AMY POSNER

Amy Posner is an MDL Safety Engineer and joined JPL in 1998. She then transferred to MDL in 2000, transferred away in 2008, left JPL in 2010, and finally returned in 2016. She earned a BS and MS in environmental and occupational health from California State University, Northridge.

■ What were some of your expectations coming to JPL?

When I started at JPL, I didn't realize that I might have found my forever home. I expected it to be like every other place I had worked, and I didn't realize exactly how diverse my experiences would be. Being able to have different experiences helps keep me engaged in what is happening around me.

■ What advice would you give young women who want to take the same career path as you?

I hope that people who are interested in a career with JPL or NASA understand that we have people here with very diverse backgrounds. We do need people with a strong STEM education, but we also need people who provide support to our missions. Working at JPL doesn't require a PhD or a degree in a hard science, and being successful at JPL isn't all about the complex analysis of mathematical equations. Everybody plays a part in mission success.

■ How important do you feel STEM education is for NASA?

I've worked hard to understand the safety struggles that JPL researchers face and have done my best to reduce the burden while maintaining compliance. We have many potential safety risks, but we also have some of the best safety solutions. As a Safety Engineer, a STEM education is valuable. In addition to coursework in chemistry, biology and physics, I completed classes in toxicology, industrial hygiene, health physics and epidemiology. While I think most of my success at JPL is because of people skills (listening, negotiating, mentoring and being assertive when necessary), some understanding of the sciences makes a big difference.

Q/A.

ANITA FISHER

Anita Fisher works with the Infrared (IR) Photonics Group to develop and characterize enhanced IR materials. She was recruited to JPL to use her biochemistry/microbiology background to develop hybrid biosensors with MDL engineers. For the International Space Station (ISS), she fabricated rapid microbial tests for drinking water and is currently fabricating a spacecraft atmosphere monitor on a silicon chip; both will benefit astronaut health. She has researched *in situ* planetary soil extraction methods, chemical analysis of those extracts, and novel approaches to extract biomarkers in planetary ices and fluidic samples.

■ How important do you feel STEM education is for NASA?

STEM education can keep us at the forefront of space exploration and Earth science; NASA recognizes the importance of STEM education and is unique because of its projects and the expertise of its 18,000 employees. The ISS/astronaut program inspires students, as does the exploration of other planets, stars and moons. I'm pleased that JPL offers internships, undergraduate and graduate programs, and assistance with creative hands-on robotic programs in schools.

■ In your opinion, from what you've seen, why should people care about the work at NASA?

The primary goal at NASA is to inspire everyone, especially students, to hear about our projects and get involved. Our missions to explore space are seen by the world and make the country proud. In particular, we all won with the success of the Perseverance landing in February 2021. I am in awe of the people who work at JPL and their exceptional accomplishments, and I enjoy the diversity and equality here. It's impossible not to care about NASA's work.

■ What advice would you give young women who want to take the same career path as you?

I would be excited to tell other young women that my path alone shows how a science career can take you places you didn't think of and that path can go in almost any direction. I wanted to work in medical research, and I did work in cancer research for many years, but I switched gears to work on astronaut health and then planetary exploration. Identify what interests you most, but then be prepared to look at all opportunities.

TO IMPROVE YOUR QUALIFICATIONS…GET INVOLVED WITH RESEARCH PROJECTS AND LOOK FOR AND LISTEN TO STRONG MENTORS

AREZOU KHOSHAKHLAGH

Dr. Khoshakhlagh joined the Infrared Photonics Technology Group at JPL in 2010 and leads the material growth and material characterization of midwave infrared (IR), long-wave IR, and two-color superlattice arrays. Dr. Khoshakhlagh is the recipient of several awards, including the Lew Allen Award for Excellence. In 2010, she received her PhD in electrical engineering from the University of New Mexico, where she worked on the design, growth, and characterization of type-II strained layer superlattice IR detectors, as well as lasers and solar cells.

■ What advice would you give young women who want to take the same career path as you?

Women in STEM are still a minority in these male-dominated fields. Some of the causes for this imbalance are stereotypes, workplace bias, and self-assessment; however, there are many ways to keep up your motivation and be successful. One of the most important factors is self-confidence and to remember that you were accepted to your position because of your qualifications and accomplishments. To improve your qualifications and provide better opportunities for your future, get involved with research projects and look for and listen to strong mentors who have traveled similar paths as the one you are trying to follow.

■ What do you think is the next big thing for NASA science?

NASA's future will continue to be a story of human exploration, technology, and science. That includes what it will take to support human exploration on Mars and beyond. We will continue to try to answer the question, "Are we alone?"

MDL KEEPING AHEAD

A CYCLE OF CONTINUOUS INNOVATION, PROCESS & PRODUCT DEVELOPMENT, AND IMPLEMENTATION.

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.

RISING TO THE CHALLENGE

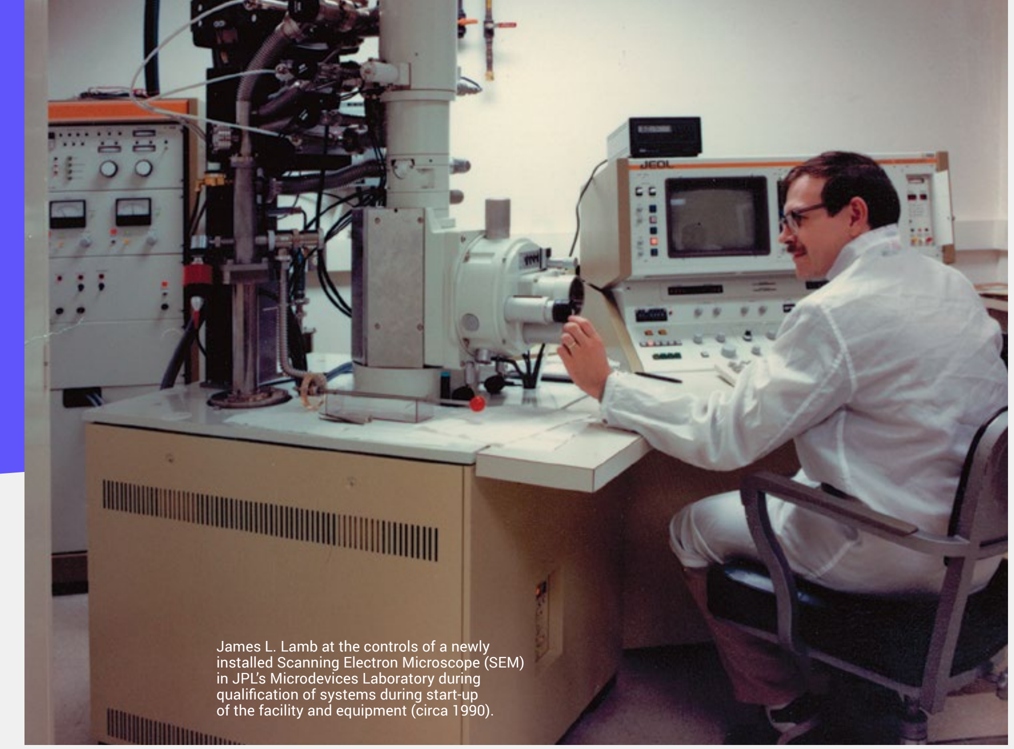
REFLECTIONS ON A CAREER ENABLING MDL

RISING TO THE CHALLENGE IS A THEME WELL REPRESENTED BY THE STORY OF JPL'S MICRODEVICES LABORATORY (MDL).

The 1982 proposal to create a semiconductor processing facility and center of excellence to develop cutting-edge technologies for instrumentation that would achieve greater science returns in smaller packages was both visionary and an investment in the future. However, support was not a given; MDL's value had to be proven and required great commitment, dedication, and perseverance.

Leadership with sustained support, commitment and vision; skilled, dedicated, creative, optimistic, and fearless personnel; well-defined processes; and infrastructure and equipment providing the requisite capabilities were, and are, critical to MDL's success.

In some respects, the story of James L. Lamb parallels the story of building a strong foundation for MDL. James was blessed with supportive parents who taught and ingrained in him a strong work ethic. He learned eagerly and enhanced his skills, taking advantage of available opportunities from his earliest school days. He had many deficiencies to overcome, but there were many there to help, including teachers, family, mentors, and colleagues. His summer jobs and his coursework were diverse, broad, and deep, which was the overall theme of James's preparation for JPL and the MDL Operations Manager position. He worked hard to obtain knowledge across many disciplines and to be an expert in one—reactive sputtering to create metastable states of materials at low bulk temperatures—which led to his hiring at JPL in 1984.



James L. Lamb at the controls of a newly installed Scanning Electron Microscope (SEM) in JPL's Microdevices Laboratory during qualification of systems during start-up of the facility and equipment (circa 1990).

James L. Lamb is the Manager of JPL's Microdevices Laboratory (MDL), the Technical Group Supervisor for the Central Processing and MDL Support Group, and a named JPL Principal in Microdevice Engineering and Implementation. He is responsible for all facility, safety, and operational issues associated with this state-of-the-art semiconductor device processing facility. A trained physicist and JPL employee since 1984, James has been associated with MDL operations since its inception. The quality of his service and leadership is evidenced by the award of two NASA Exceptional Service Medals (1995 and 2011).

His construction skills, generalist science knowledge across many disciplines, and ability to communicate between construction personnel and scientists were recognized when the Thin Film Physics Laboratory was established, and in 1986, he was brought in to help with the construction of MDL.

In a mere 25 years (1970-1995), through training, hard work and experience, James progressed from a chemistry set, microscope, and electronic test lab in the basement of his home in high school, as well as unsuccessful (from failed materials) home-built rockets with match-head fuel, to a semiconductor processing lab manager. Another 26 years of continuous learning followed and involved not only acquiring new equipment with evolving capabilities but also transitioning the lab from R&D activities to deliveries.

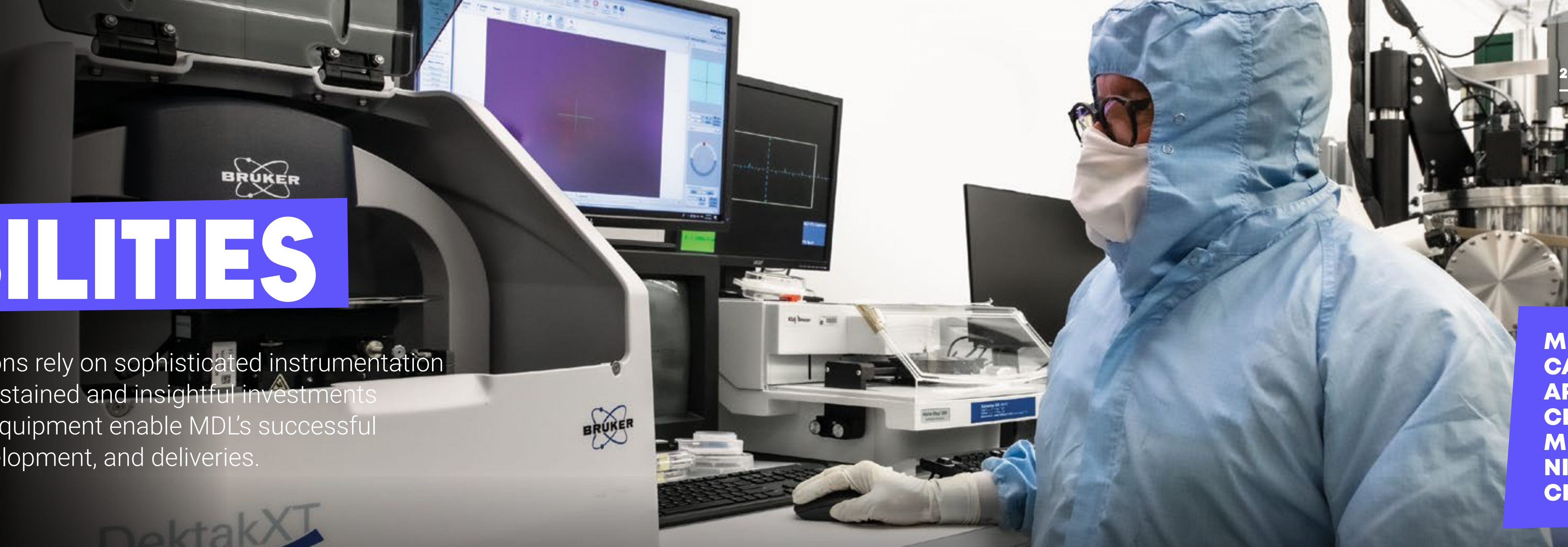
Some of the early deliveries from MDL exemplify the differences between the R&D and delivery disciplines. R&D emphasizes creativity, the ability to try new things quickly, and establishing proof of concept. Delivery activities emphasize the traceability of parts and materials, consistency, and reproducibility. This difference was learned when MDL developed a process for the ultraclean and electrostatic discharge (ESD)-free dicing of Cassini charge coupled device (CCD) imagers. Early development identified some possible sources of ESD, but preliminary testing indicated that the initial techniques showed no damage; therefore not all possible ESD corrective measures were implemented. After the process was locked in, later testing indicated some deep-level ESD damage. The team had a fix in hand and immediately implemented the change. However, this is not the flight deliverable process. Instead, the team had to return to the original setup and show that they could duplicate the damage. Only then could they implement the changes, test the device, and show that the damage had been eliminated. A one-day fix took two weeks, but it was adequately documented. One cannot just fix issues with flight deliverables; rather, one has to demonstrate an understanding of the problem, fully document that problem, and fully document the fixes and successful outcomes.

This process takes time. However, it is valuable if one has to reproduce a delivery 6 months or even 16 years later with different people (as was the case with a sidecar electronics wire bonding process fix). It is noteworthy that MDL is not just a building with normal independent services. Rather, it is a complex system in which all of the service elements are linked. This connection is necessary to allow the hazardous production materials (HPMs) and acutely hazardous production materials (AHMs) required in the fabrication of semiconductor devices to be handled and utilized safely. It involves configuration control and Hazard Operability Assessments for all operations within the facility and implementation of the MDL Safety Triad of Separation, Monitoring, and Control (both engineering and administrative). This continued oversight of facilities, safety, equipment, and processing operations has enabled MDL to be successful.

Today, MDL has demonstrated the initial vision and has established itself as a technology powerhouse of research, development, and delivery across the electromagnetic spectrum, from the soft X-ray regime through the ultraviolet, visible, near-infrared, mid-infrared, far-infrared, submillimeter and millimeter regions of the spectrum. MDL also has made contributions to other technology areas. Building a strong foundation of infrastructure, equipment, and processes was a necessary ingredient to achieve these results in the past. It will continue to be a necessary condition for the future, as well.

> **Many people have contributed to the success of MDL, and MDL has been a part of the successes of myriad people since its inception. Among them, though, James L. Lamb stands out for his unique role in helping to establish and sustain the lab for decades, contributing from the early days of its physical construction to today as Operations Manager. His decades-long dedication has forged a legacy of excellence that will sustain MDL for years to come. —Siamak Forouhar, MDL Deputy Director**

FACILITIES & CAPABILITIES



The new Dektak XT profilometer is used in each step of the device fabrication process, such as measuring etch and deposition step heights, profile uniformity, and 3D profile mapping.

MDL's technical implementations rely on sophisticated instrumentation in ultraclean environments. Sustained and insightful investments in people, infrastructure, and equipment enable MDL's successful and substantial research, development, and deliveries.

MDL'S INFRASTRUCTURE CAPABILITY INVESTMENTS ARE STRATEGICALLY CHOSEN TO ALLOW MDL TO FLEXIBLY AND NIMBLY MEET FUTURE CHALLENGES.

MDL, now in its 31st year of operation, is a specialized laboratory within JPL that invents, develops, and delivers novel microdevices and critical microdevice technologies not available elsewhere. MDL fills the critical gap between the outstanding work done by PhDs and postdocs at universities and the tight specifications of off-the-shelf components available commercially. MDL staff have the creativity and technical acumen to create first-of-their-kind, breakthrough microdevices that access new observables that broaden NASA's understanding of the cosmos, and it simultaneously maintains the rigor and critical requirements needed for the end-to-end fabrication and delivery of these space-quality microdevices for NASA/JPL missions.

MDL is enabled in large part by JPL institutional investments that pay for the safe operation of the cleanroom facility and infuse the laboratory with funds for the acquisition of cutting-edge semiconductor capital equipment. This institutional support ensures that anyone working on a NASA/JPL project or task, from flagship flight projects to small, proof-of-concept demonstrations, can have free access to the tools within MDL. This investment has led to a diverse group of around 100 tasks being conducted in the facility on a regular basis. MDL is maintained by a staff who are highly experienced in facilities, safety, and equipment engineering and who also provide the experience necessary to enable the safe and effective implementation of breakthrough ideas and novel materials systems/processes.

MDL is designed for the end-to-end fabrication on substrates up to 150 mm (6 inches) in diameter (with some 200-mm [8-inch] and 225-mm [9-inch] diameter exceptions for select process steps) and subsequent characterization of the fabricated microdevices. MDL's focus on making the front-end sensing elements of instruments better across the electronic spectrum, from the soft X-ray regime to the millimeter (mm) regime, requires that it deal not just in silicon but also in gallium arsenide, gallium antimonide, gallium nitride, and superconducting materials, as well as in different wafer diameters and thicknesses. In addition, new materials and equipment capabilities are continuously being introduced. This ability to handle and process diverse material families and substrate types in a controlled manner is one of the unique features of the MDL facility.

The 2020-2021 time period was unlike any other in MDL's history. The initial onset of COVID-19 resulted in a nearly two-month safe idling of the cleanroom from mid-March until mid-May, during which no processing was allowed. A second shutdown was necessitated by the Bobcat Fire in early September due to excessive particulate intake, leading to a loading of the pre-filters to the cleanroom. R&D tasks were also suspended from November to February due to the COVID-19 holiday surge. Despite these challenges, the MDL cleanroom was in a safe and ready state throughout. In fact, the MDL cleanroom underwent substantial configuration changes, facility renewals, and equipment installations enabled by the MDL Central Processing and Support Group, even during these shutdown and slowdown periods. The group was highly engaged throughout the entire period, ensuring safe operation with minimal interruptions while maintaining "safe-at-work" practices. Custom online scheduling methods for cleanroom access were developed. In all, processing during the period was very successful, with flight deliveries and R&D tasks slowed but still enabled while construction projects and routine maintenance took place.

A key construction project undertaken during this period was the design, construction, and soon-to-be qualification of a new ISO 5, class 100 cleanroom space. This area was formerly a space dedicated to sample preparation steps, such as lapping and polishing, as well as electroplating. It is now being prepared for the installation of up to three new systems, the first of which will be an SPTS Omega LPX deep reactive ion etcher with Rapier source for etching silicon. While deep reactive ion etching (DRIE) is a workhorse technique at MDL and is useful for micromachining microvalves, through silicon vias, shadow masks, etc. for a wide variety of needs, this machine offers a substantial improvement in MDL's DRIE capabilities, producing smoother etched sidewalls at lower temperatures to be more compatible with resist processing.

Motivated by a desire for device yield enhancements for large-scale fabrication runs, investments in surface preparation and cleaning equipment were made in 2020 for subsequent installation in 2021. These investments included a custom-designed 8-foot solvent wet bench for processing batches of 6-inch wafers and an S-cubed spray liftoff and photoresist removal tool. Liftoff is a very good technique for patterning materials that do not have convenient plasma etches (such as gold and other metals), but traditional liftoff processing in beakers leads to particulates and "flag"-type defects from metal that has redeposited or failed to break away. These two new equipment investments will help ensure that the starting wafer surfaces are extremely and uniformly clean from the start and that the undesired metal is reliably and safely carried away.

MDL has an extensive suite of deposition capabilities that includes, but is not limited to, Tystar low pressure chemical vapor deposition of low stress silicon nitride, Oxford inductively coupled plasma (ICP) plasma-enhanced chemical vapor deposition of dielectrics, load-locked sputter and electron beam (e-beam) evaporator tools for metals and dielectrics, and two atomic layer deposition systems for oxides, nitrides, fluorides, borides, and combinations thereof. To continue MDL's tradition of breakthrough material development and nanoscience, two investments were made in 2020 and brought online in 2021 to bring capabilities together in new, integrated ways. First, a custom system bringing atomic layer deposition and metal evaporation together in one chamber was created for the fabrication of multilayer film stacks for the tailored design of mirror and/or filter coatings on detectors. Second, a confocal sputtering system for manganese doping of superconductors was purchased and installed in a sister laboratory for use by MDL researchers.

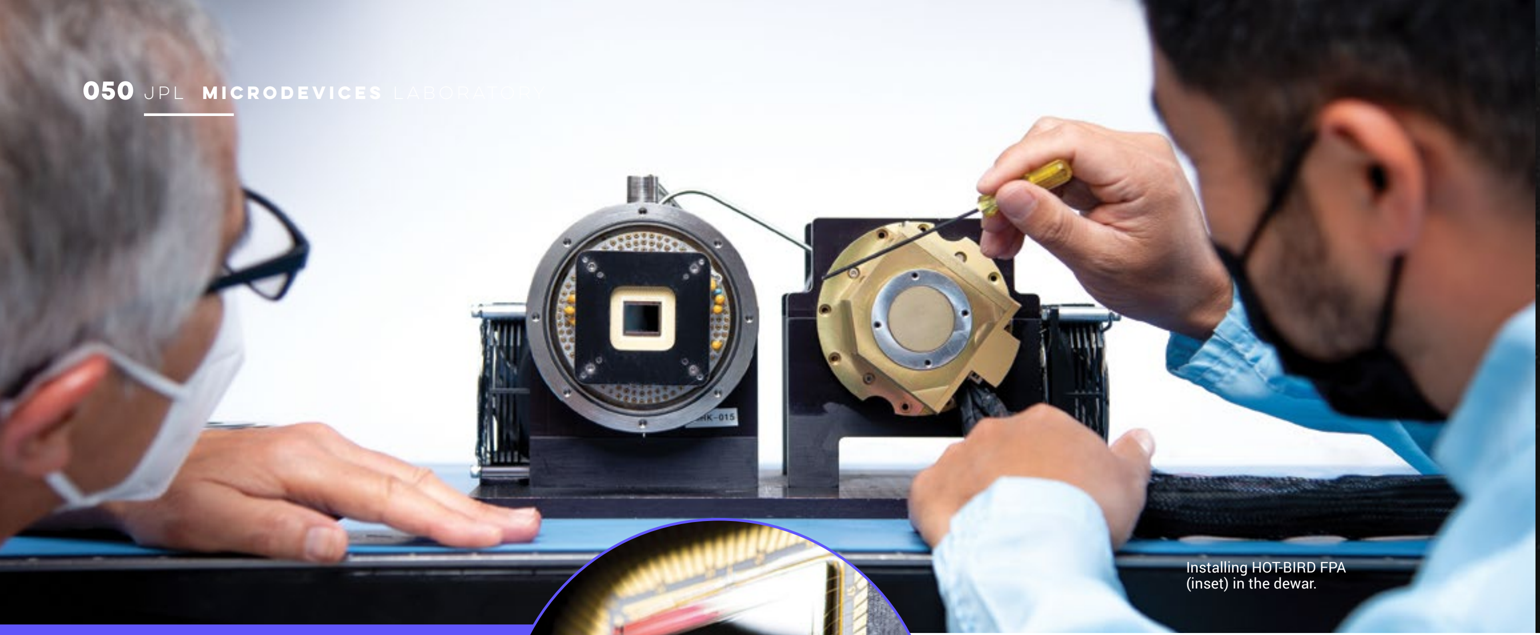
MDL continues its achievements in greyscale grating fabrications with our e-beam lithography investments, most recently with the installation of the third upgraded replacement system in 2017. This new system has state-of-the-art nanoscale patterning capabilities on wafers of up to 225 mm (9 inches) in diameter and facilitates patterning on curved surfaces. We also expanded our patterning capabilities via steppers (EX3, EX6, and I-line) and replaced an older I-line stepper with a maskless system in 2019/2020. Our fluorine and chlorine dry etching capabilities evolved from reactive ion etching (RIEs) to ICP RIEs, then to deep silicon etching (DRIE) and, most recently, atomic layer etching (ALE). Deposition system investments are also evolving: liquid phase epitaxy (LPE) was replaced by metal-organic chemical vapor deposition (MOCVD), which was then replaced by molecular beam epitaxy (MBE) super lattice growth capabilities for the fabrication of semiconductor lasers. Our MBE capabilities include a unique silicon MBE with ultra-high vacuum evaporation capabilities for 200-mm (8-inch) diameter wafers, enabling delta-doped ultraviolet charge coupled devices. Additionally, we have invested in III-V (Sb) MBE wafer processing technologies that allow near-infrared (IR), mid-IR, and long-wave-IR focal plane arrays and a high operating temperature barrier IR detector (HOT BIRD) design that can operate at higher cryo temperatures.

MDL's wide variety of characterization equipment includes a cold cathode scanning electron microscope, atomic force microscopes, X-ray diffraction, an upgraded X-ray photoelectron spectroscopy system, an extended-range ellipsometer, Fourier transform IR capabilities, and a 1.7 K cryo probe station. Investments have also been made in enhanced optical and IR inspection microscopes for both characterization and alignment.

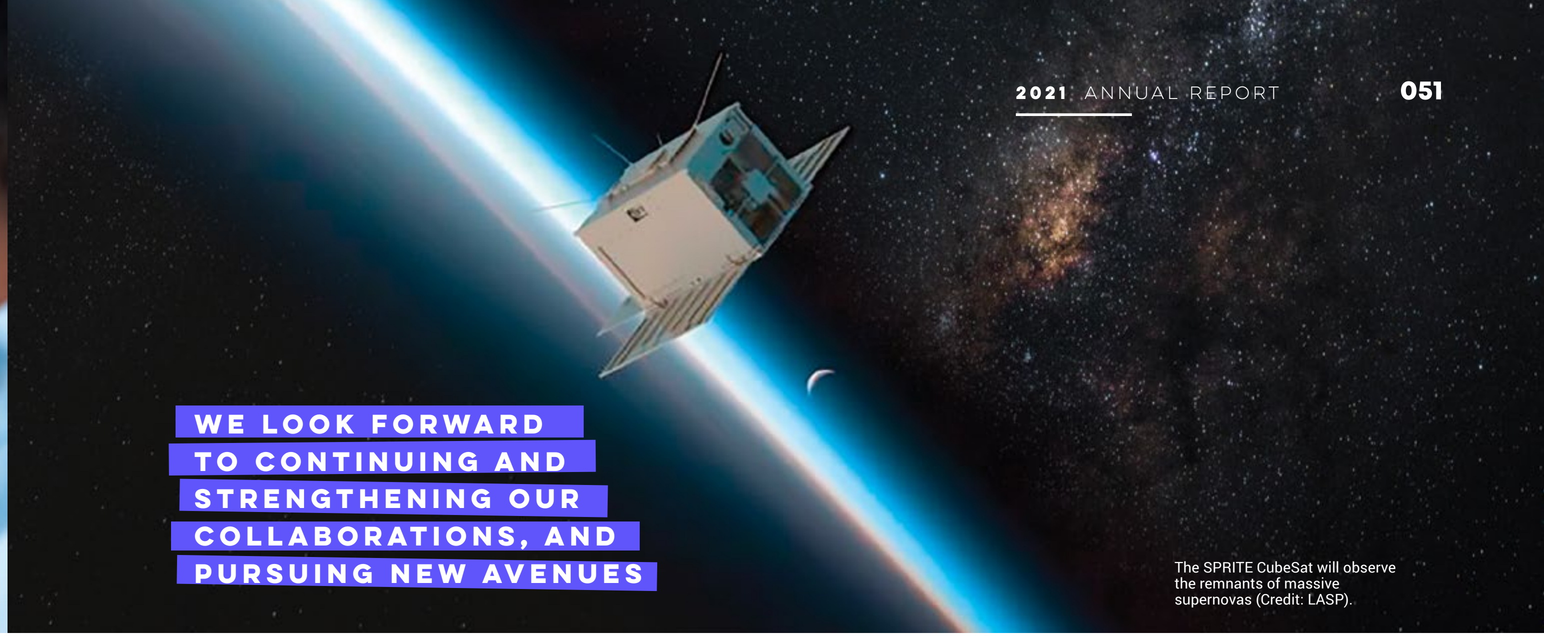
Although MDL's infrastructure has been continuously maintained and improved, some systems have successfully served MDL since the original construction of the building and require upgrade and renewal. The first of these support systems to be upgraded was the inorganic exhaust blower pads, one of which was addressed and completed in late 2021, and the second of which will follow closely behind in 2022. Improvements to the control of the building relief dampers and compressed dry air systems, as well as insulation enhancements to the process cooling water system, were also completed in 2021. Lastly, a building-wide power shutdown was initiated over the winter holidays to service the switch bank to an emergency generator supporting MDL's life safety systems. Future renewals planned for 2022 include a redesigned humidity control system, hot/cold deck, and blower fan bank assembly for the primary air handler intake for the building (AH1).

MDL's operations and infrastructure are sustained and enabled by the Central Processing and MDL Support Group, which is led by Technical Group Supervisor and MDL (Operations) Manager James L. Lamb. The dedicated professionals who make up this group not only bring technical expertise to their own specialties but also work as a team, augmenting each other's skill sets and offering processing expertise and capabilities to others. With a consistent focus on continuous improvement, the group's responsibilities include configuration control, facilities and safety oversight, maintenance, and new equipment specification and installation.

MDL IS A 4,422 SQUARE METER (47,600 SQUARE-FOOT) FACILITY WITH CLEANROOMS AND TEST LABS



Installing HOT-BIRD FPA (inset) in the dewar.



The SPRITE CubeSat will observe the remnants of massive supernovas (Credit: LASP).

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

MDL COLLABORATIONS

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 or cross-organization at JPL produces mutual benefits that are greater than the sum of their parts.

An infrared image captured by a HOT-BIRD FPA.

COLLABORATION FUELS RAPID TECHNOLOGY INFUSION WITH REDUCED RISK

In collaboration with MDL technologists, JPL's Mission Assurance group is pioneering a new approach to technology qualification for future space missions. Historically, new devices with low technology readiness levels (TRLs) are not considered for space-based operations unless the added benefit greatly outweighs the associated cost and risk, which is often not the case. This issue becomes circular because science mission requirements demand instruments that need the performance capability of new technology. Bridging the gap between technologists and end users is a long and challenging process. The early evaluation of new technology on a path toward space applications will help to develop screening guidelines and qualification criteria for new devices desirable for space use. This program, with its highly collaborative, cross-project and cross-division information exchange, enables the proactive identification of the limitations and failure modes of new devices. This information will help designers and project teams in selecting devices and will reduce risk, cost and schedule.

Several novel devices for future missions are currently being assessed as part of this effort. For example, a collaboration is underway to raise the TRL of the high operating temperature barrier infrared detector (HOT-BIRD) focal plane arrays (FPAs) developed by MDL. This FPA provides lower cost and high performance with excellent uniformity, which is very attractive for future Earth missions. The outcome will help in developing the process for the early evaluation of new technologies and foster close collaboration between divisions.

The Deep Space Optical Communication (DSOC) project employs single photon detectors in its ground-based receiver to achieve photon-level sensitivity. This technology has the potential to reduce size, weight and power SWaP for future space-based DSOC missions; however, its performance in the space environment remains unknown. This collaboration aims to raise the TRL for path to flight by evaluating radiation, thermal, and lifetime performance through tests.

Photonic integrated circuits (PICs) are projected to be an enabling technology for many science and communication applications, but, like the photon detectors, reliability and performance in the space environment are unknown. Radiation testing of state-of-the-art indium phosphide (InP) integrated transmitters (seed laser, amplifier, and modulator) and silicon/silicon nitride (Si/SiN) waveguides are currently underway. Technology for ocean world exploration is also being explored. Polymer-based 3D printing devices have shown promise but have undesirable characteristics, such as out-gassing, low stability, interaction with fluids in the environment, and susceptibility to radiation effects. MDL is looking at how to address these known issues to make the technology viable for future missions.

Hardware testing in the space environment is key to raising TRLs and demonstrating reliability; however, disseminating information to the JPL community is also vital to reducing the path to flight time. The Mission Assurance Group and MDL facilitate discussions between scientists, technologists, and reliability engineers to understand mission objectives, requirements, and viable technology earlier in mission life. Regular talks are also hosted with industry, academia, and JPL principal investigators to keep the community up to date on the current state of the art.

The impact of this new approach, led by a collaboration between JPL's Mission Assurance Group and MDL, goes beyond streamlining a path to flight for new technology; it will also establish JPL as an industry leader in novel space-based technologies (e.g., PICs) at the device and system levels and increase cross-organizational collaboration, opening the door for further technology development and high-performance science instruments at reduced risk and cost.

UNLOCKING INNOVATION THROUGH COLLABORATIONS

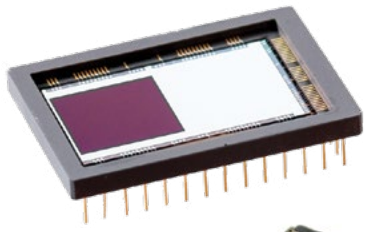
SPRITE+COATINGS

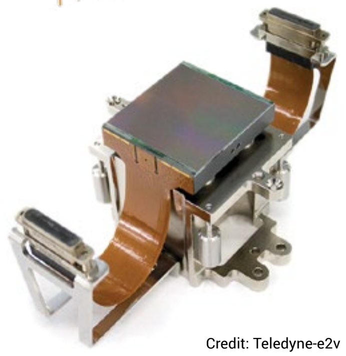
The development of next generation UV mirror coatings at MDL has continued in support of the Supernova remnants / Proxies for Reionization / and Integrated Testbed Experiment (SPRITE) CubeSat (PI: Brian Fleming at CU Boulder). SPRITE is NASA's first 12U astrophysics CubeSat, and is designed to perform imaging spectroscopy in the far-UV (100-175 nm) in support of scientific observations associated with the mapping of shock emission from supernova remnants, and determining the escape fraction of hydrogen ionizing radiation from star-forming galaxies. SPRITE is also a technology testbed for protected aluminum mirror coatings that are relevant to the large ultraviolet, optical, infrared (LUVOIR) flagship mission concept. These coatings combine new lithium fluoride processes developed at NASA GSFC with thin encapsulation layers deposited by atomic layer deposition (ALD) at MDL.

The combination is designed to improve both the short wavelength performance and the long-term stability of the full mirror coating. The coating of SPRITE's optics is occurring in 2021 with a planned launch in late 2022. SPRITE's primary mirror will be the largest optic coated to date by the JPL ALD method. For future applications, the scaling of this coating technology is also being pursued as part of an ongoing NASA Strategic Astrophysics Technology program (JPL PI: John Hennessy).

UV & UV/VISIBLE DETECTORS

JPL and Teledyne-e2v have formed a strategic partnership to develop advanced detectors with high quantum efficiency, wide and tailorable spectral range, photon counting, uniformity, and generally high performance for future space missions. In particular, this collaboration involves the MDL team of experts in advanced UV and UV/Visible detectors to combine Teledyne e2v's image sensor technologies for scientific imaging and JPL's ultraviolet detector technologies in the development of science grade UV sensitive image sensors. The MDL team and Teledyne-e2v previously have developed detectors under successful R&D efforts and deployment to suborbital programs. The partnership is enabling potential new science through multiple mission concepts and proposals.





Credit: Teledyne-e2v

MDL NEXT POSTDOCS

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

MDL was established with the goal of providing capabilities to develop components, sensors, and instruments for the JPL/NASA space program. For MDL to maintain and excel at its current leadership role, it is essential to identify and engage the best researchers and programs that will utilize and expand MDL's capabilities while focusing on NASA and JPL's future scientific and technical goals. The postdoctoral program at MDL has been a great channel for recruiting the next generation of MDL technologists.

GHAZALEH SHIRMANESH

I joined MDL as a postdoctoral fellow in October 2020 after finishing my PhD in applied physics in Professor Harry Atwater's group at Caltech. At MDL, my work has focused on integrated photonics, specifically input/output coupling for photonic integrated circuits (PICs). PICs can provide unique capabilities with uses in astronomy, planetary science, and free space communications. To fully exploit the capabilities of PICs and convert them into cutting-edge system-level components, it is crucial to have an interface that can flexibly couple light to the PIC.

PICs typically use fiber-based coupling solutions. However, these systems do not scale favorably towards large numbers of channels. To go beyond the size, weight, and scaling limitations of fiber-based systems, solid-state lithography solutions can be used.

Typically, the beam received at the focal plane of a telescope is composed of different orthogonal, spatially overlapping, and co-propagating modes. Coupling this beam to the single-mode waveguides on a PIC requires a multi-mode to single-mode transformation. Metasurface photonic lanterns (MPLs) offer an ultracompact solution that decomposes a complex multi-mode input optical signal into an array of single-mode beams. The obtained Gaussian beams with fundamental modes can then be collected by single-mode waveguides on the photonic chip.

The number and spatial distribution of demultiplexed channels can be flexibly designed. Furthermore, the operating wavelength of MPLs can be extended to the visible, near-infrared and infrared.

In PIC spectrography, having many outputs creates challenges for existing outcoupling techniques. Lithography-based output coupling solutions provide low size, weight, power and cost (SWaP-C) output coupling approaches that can address large numbers of output ports. The modern simulation techniques and state-of-the-art lithography tools available at MDL for rapid fabrication and integration with PICs enable output coupling schemes with wide optical bandwidths, high throughput, low crosstalk, appropriate polarization characteristics, and flexible output port counts.

PETER WEIGEL

I received my PhD in electrical engineering from the University of California San Diego in 2018.

I joined MDL in early 2019 as a postdoctoral fellow in the MDL Next program and was promoted to a full-time position in the spring of 2021.

Since joining JPL, my primary focus has been the pursuit of photonic integrated circuits (PICs) for specific applications where compact, lightweight technologies are needed. While at JPL, I developed thin film silicon nitride and lithium niobate waveguide fabrication processes, variable silicon nitride and silicon oxynitride film deposition capabilities, and a niobium nitride-on-lithium niobate thin film process.

I have used these fabrication methods to develop and demonstrate broadband, passive laser frequency tracking for high-precision segmented telescope aperture stabilization, lithium niobate photonic mesh arrays for photonic sensing, and on-chip single photon detection. These core technologies are currently being pursued as the foundation of system-level architectures designed around PICs and geared towards astronomy and astrophysics applications, such as exoplanet detection, high-resolution imaging, and spaceborne gravity measurements.

ERIC KITTLAUS

After finishing my PhD in applied physics in Professor Peter Rakich's group at Yale, I came to MDL as a postdoctoral fellow in 2019, and I recently joined as a permanent staff member. My work at MDL applies photonic device technologies to develop new capabilities in microwave- and laser-based sensing. Specifically, I am interested in systems that combine both optical and electrical control to perform tasks that are not easily done with either system alone.

For example, we recently demonstrated the first practical acousto-optic modulator in a silicon photonic circuit. This type of device uses gigahertz (GHz)-frequency electrical signals to manipulate the frequency, path, or intensity of light on the surface of a tiny silicon chip. To achieve this type of interaction between electrical and optical signals, we use hypersound waves as an intermediary. The device works by implementing tiny piezoelectric transducers on top of a silicon chip. Using these transducers, we can generate electrically driven acoustic waves that are launched toward light guided in buried waveguides (or "photonic wires"). These hypersound waves deform the material through which the light travels, producing an electro-optic mixing or "modulation" effect. By controlling the electrical drive, we change the strength and character of this modulation, producing electro-optic coupling between radio frequency (RF) and optical components that are spatially separated. Modifying the device geometry allows tailoring of the specific operation, ranging from control of the intensity and phase of optical signals to creating unidirectional valves, called optical isolators, for light.

These types of chip-based acousto-optic devices may be useful for a variety of NASA applications. At a basic level, they provide a means to reduce size and power requirements while permitting new functionalities for spaceborne optical sensors, such as lidars and laser metrology instruments. Variations on this technique can allow active optical devices operating on portions of the electromagnetic spectrum not accessible with existing integrated photonic device technology. From a more general standpoint, adding acousto-optic interactions to the suite of existing technologies for chip-based photonic circuits will facilitate the development of complex, multi-functional integrated photonic devices.

Another area of focus is the generation of low-noise microwave and millimeter-wave signals using photonics. This is a very intriguing area of research, since photonics-based signal generation can potentially outperform conventional electronic synthesizers in terms of noise level, size, and power consumption by orders of magnitude. Moreover, low-noise signal generation at high frequencies is directly applicable to pulse-compressed scientific radar instruments such as JPL's Vapor In-cloud Profiling Radar (VIPR), where the noise level of the transmitted signal sets the achievable dynamic range for atmospheric measurements. Recently, we developed a photonics-based synthesizer based on frequency mixing of two commercial ultralow-noise lasers. This source provides tunable signal generation from 1-104 GHz with extremely low noise and low power consumption. Notably, we implemented this synthesizer in a 95-GHz radar test bench, demonstrating its benefit to radar through outdoor measurements. This was the first time this type of synthesizer, which uses two continuous-wave lasers, was applied to radar, and we are very excited about the future of this technology for enhancing measurement capabilities at higher frequency bands.

MOHAMED SABRY

I completed my PhD with Professor Romuald Houdré at the Swiss Federal Institute of Technology in Lausanne (EPFL) and joined MDL as a NASA Postdoctoral Program Fellow in 2019. My work encompasses the development of next-generation solid-state deep-ultraviolet (deep-UV) laser sources for space applications.

Deep-UV light sources are essential for spectroscopic instruments incorporating advanced measurement techniques, such as Raman spectroscopy and laser-induced fluorescence. On planetary missions, these tools enable the assessment of habitability and the search for life through the non-destructive detection and compositional analysis of organics, biosignatures, and other chemical species of interest.

Coherent deep-UV source development faces technological hurdles. Current state-of-the-art instruments rely on gas-based lasers, but a solid-state deep-UV laser based on nonlinear frequency conversion offers >100x volume reductions and 10x higher output power levels under continuous-wave operation, along with improved beam quality, higher power efficiency, and a longer lifetime. I have been developing chip-scale technology for beta-barium borate (β-BBO), a nonlinear crystal that is key to this approach. It features ultra-broad transparency spanning the near-infrared to the deep-ultraviolet wavelength range. The birefringent nature of the crystal facilitates phase matching of second harmonic generation to the deep-UV range by compensating for the intrinsically strong material dispersion towards shorter wavelengths. β-BBO is hygroscopic, making it challenging to process, but I have recently demonstrated sub-micron scale lithographic patterning of β-BBO using a novel anhydrous fabrication process, enabling visible and UV-range photonic components. I am currently advancing β-BBO thin-layer technology towards obtaining β-BBO-on-insulator films with optimized properties for deep-UV generation.

With this development, compact coherent deep-UV light sources will become readily available for *in situ* instruments on upcoming planetary missions. This unique technology will also serve a wide range of applications beyond light sources, whether in the deep-UV wavelength range or for multi-octave-spanning devices.

KEEPING MDL AT THE CUTTING EDGE

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.

ADV. OPTICAL & ELECTRO-MECHANICAL MICROSYSTEMS

The Cabeus impact crater near the south pole of the Moon hosts permanently shadowed regions that contain water ice. Such regions have the potential to provide ample source material for the *in situ* extraction of oxygen propellant and other resources needed for a sustained human presence on the lunar surface. Credit: NASA/GSFC/Arizona State University.

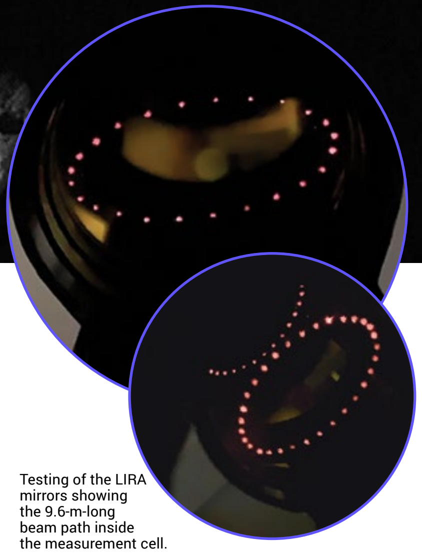
LASER SPECTROSCOPY

LIRA INSTRUMENT MEASURES TRACE WATER

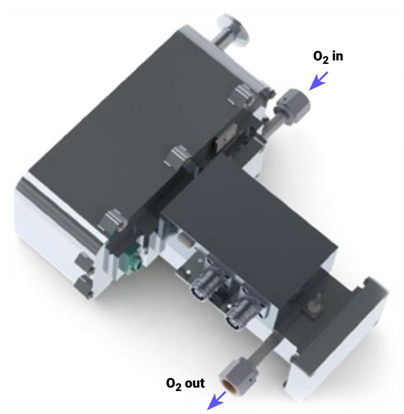
One of the great challenges presented to NASA this decade is to return humans to the Moon and ultimately establish a sustained human presence on the lunar surface. *In situ* resource utilization (ISRU) is a key element of NASA's strategy to achieve this goal, and a major component of ISRU operations will be the extraction and storage of oxygen propellant from ice and other compounds in lunar regolith. Propellant-grade oxygen must be extremely dry, with water contamination on the order of a single part per million, so NASA needs robust sensors capable of validating propellant purity at these stringent levels.

To help NASA rise to this challenge, MDL engineers have developed the Laser *In situ* Resource Analyzer (LIRA) to integrate with propellant generation systems being developed by partners at NASA's Johnson Space Center. LIRA is adapted from JPL technology initially developed to answer important scientific questions about the atmosphere of Mars; this technology has successfully operated on the Curiosity rover for more than eight years.

The NASA Game Changing Development Program supports the LIRA project as part of the Lunar Surface Innovation Initiative. The LIRA project is managed by Ryan Briggs and the team includes MDL engineers Nicholas Tallarida and Mathieu Fradet, as well as Lance Christensen from the JPL Science Division.

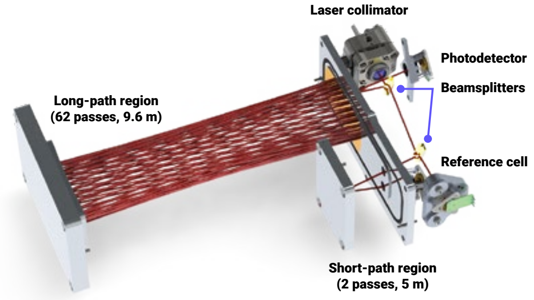


Testing of the LIRA mirrors showing the 9.6-m-long beam path inside the measurement cell.



Rendered views of the exterior and interior optical configuration of the LIRA instrument.

THE LIRA SENSOR WILL CONTINUOUSLY MONITOR TRACE WATER LEVELS IN OXYGEN PROPELLANT STREAMS OVER A BROAD RANGE OF FLOW PRESSURES AND TEMPERATURES



The Laser *In situ* Resource Analyzer (LIRA) is a laser absorption spectrometer with a tunable semi-conductor source at a wavelength of 2.6 μm. LIRA includes a multi-pass optical cell with a 9.6-m path length, enabling it to accurately measure water vapor at sub-part-per-million levels in oxygen propellant.

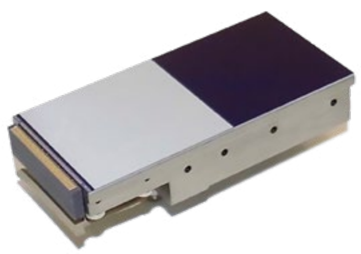
ADV. DETECTORS, SYSTEMS & NANOSCIENCE

This artist's conception portrays two neutron stars at the moment of collision. New observations confirm that colliding neutron stars probably produce short gamma-ray bursts. Credit: Dana Berry / SkyWorks Digital, Inc.

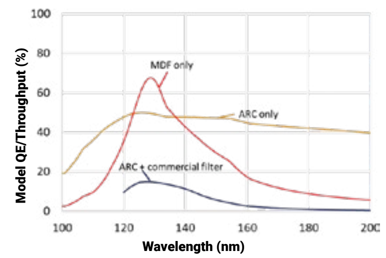
UV DETECTORS

DETECTOR-INTEGRATED METAL DIELECTRIC FILTERS

MDL UV DETECTOR TECHNOLOGIES ARE ENABLING ASTROPHYSICS SCIENCE IN COMPACT INSTRUMENTS



Dorado baselines a large-format, delta-doped UV CCD. The 2k × 2k frame transfer device has a 15 μm pixel pitch allowing for wide-field on-sky imaging.



Plot showing throughput scenarios for delta-doped UV-detector with an antireflection coating (ARC; gold line), an ARC together with a commercial bandpass filter (blue line), and a device-integrated MDF (red line).

DORADO SMEX STEP 2

MDL is currently working on Dorado, an Astrophysics Small Explorer (SMEX) mission concept currently in Phase 2. The mission is led out of Goddard Space Flight Center by Principal Investigator Dr. Brad Cenko. Dorado would be a small satellite (SmallSat; typically defined as having a mass ≤250 kg) operating in low Earth orbit. The mission's primary objective is to isolate and characterize the ultraviolet (UV) emission from gravitational wave (GW) sources, addressing a critical gap in multi-messenger astrophysics. This emerging field takes advantage of coordinated observations of astronomical events with different signals. Perhaps the most famous example of multi-messenger astronomy is associated with a 2017 event known as GW170817, in which 70 telescopes and observatories all set their sights on a binary neutron star merger, capturing data across the entire electromagnetic spectrum. Dorado will be dedicated to early (i.e., within a few hours) ultraviolet observation of such events.

The Dorado payload would include a UV camera as the primary science instrument, to be developed and delivered by JPL; the baseline detector for Dorado is MDL's UV-optimized 2D-doped silicon detector, specifically a large format charge-coupled device (CCD). The detector would be optimized for the Dorado bandpass with state-of-the-art device-integrated metal dielectric filters (MDFs) developed by the Advanced Detectors, Systems, and Nanoscience Group.

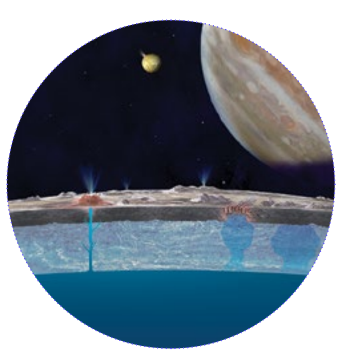
The integrated MDF is similar to commercial bandpass filters components that offer high transmission in the target wavelength range together with high out-of-band rejection ratios. This type of performance is critical for missions like Dorado that are making observations of faint UV targets in the presence of a high visible background. Integrating the MDF/bandpass filter as a detector coating (i.e., deposited directly on the detector) yields better/higher overall in-band throughput vs. using a separate optical element. An example is shown in the above right plot.

CHEMICAL ANALYSIS & LIFE DETECTION

The tip of an electrophoresis capillary specially designed by JPL partners at SCIEX corporation for spraying liquid samples into a mass spectrometer.

CAPILLARY ELECTROPHORESIS ANALYZER

NASA's search for life on other worlds is a main driver of future missions to ocean worlds like Europa and Enceladus. This search will require instrumentation capable of performing cutting-edge *in situ* chemical analyses to determine if life was the source of a particular chemical fingerprint. MDL has been rising to this challenge by developing hardware and methods to meet these needs. The challenge is twofold, as it requires both technical and scientific developments. Our work focuses on addressing both of these challenges. On the technical side, we are developing hardware specifically meant for performing *in situ* liquid-based analyses. On the science side, work progresses to help identify which biosignatures are the most powerful and likely to be detected. To be prepared for the unexpected, we are also developing analytical strategies to detect the widest possible range of compounds.



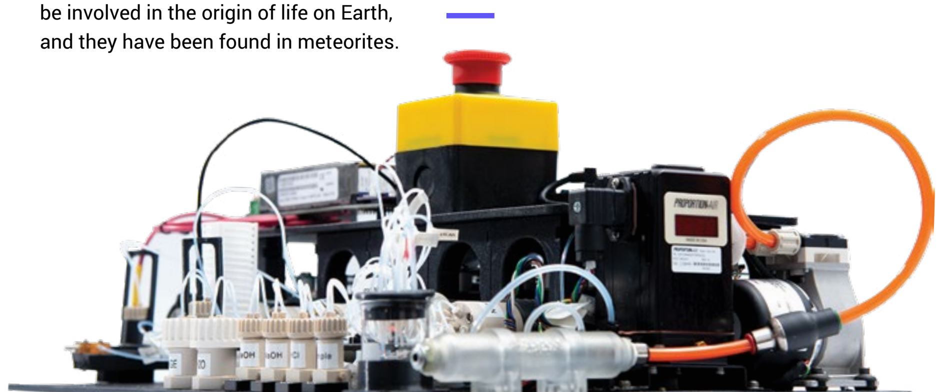
This illustration of ridges and fractures on Europa shows one possible way that water could reach Europa's surface.

The liquid analysis hardware is an automated, portable capillary electrophoresis instrument that can be coupled to multiple detectors, allowing the implementation of the broad array of methods we have developed. The use of liquid-based electrophoretic separation in the search for life is particularly powerful, enabling the analysis of a wide range of soluble organic and inorganic compounds. To cast the widest possible net within the chemical space, we use three detection systems.

Laser-induced-fluorescence detection allows for the most sensitive possible analysis of amino acids, which the astrobiology community considers one of the strongest biosignatures. Mass spectrometry enables the detection of a wide range of organic compounds and the identification of unknown species in a sample. Finally, contactless conductivity detection (C4D), one of our newest analytical methods, is ideal for detecting inorganic ions, which can provide information about the chemical environment of the sample, as well as the potential for habitability. Specifically, C4D can be used to detect organic acids, a biologically important class of molecules that are essential for all metabolic and energy-related processes. These molecules have been suggested to be involved in the origin of life on Earth, and they have been found in meteorites.

A DEDICATED GROUP OF SCIENTISTS AND TECHNOLOGISTS IS WORKING TO UNDERSTAND THE MOST RELIABLE SIGNATURES OF LIFE AND TO DEVELOP INSTRUMENTS TO DETECT THOSE SIGNATURES

C4D allows for the fast analysis of more than 21 compounds, is robust towards high salinity, and is fully compatible with our life detection instrumentation. We have demonstrated a fully automated, portable capillary electrophoresis analyzer that is capable of these three modes of detection. The system was demonstrated in the lab and in the field by analyzing samples collected from the Pacific Ocean. The ocean samples are a natural analog to the ocean worlds NASA hopes to explore, and they highlight the instrument's capability of analyzing samples that contain levels of salts similar to those expected during potential future missions. Thus, the work of today prepares us for the future.



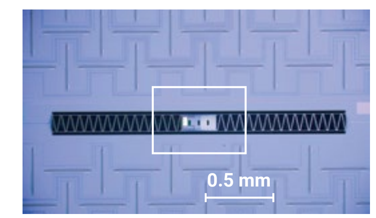
JPL's first complete brassboard prototype for end-to-end capillary electrophoresis analysis, which uses a hollow glass capillary as the separation element. This design has been validated and is the first system capable of directly interfacing with mass spectrometry detection.

The SPIDER instrument prior to launch, near McMurdo Station in Antarctica.

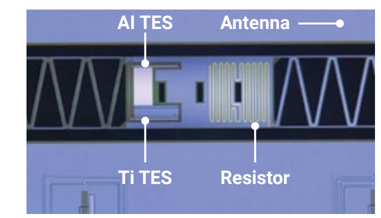
SUPERCONDUCTING MATERIALS & DEVICES

TRANSITION-EDGE SENSOR

AN MDL-DEVELOPED SENSOR HAS ENABLED A MISSION TO UNDERSTAND WHAT HAPPENED JUST AFTER THE UNIVERSE CAME INTO BEING

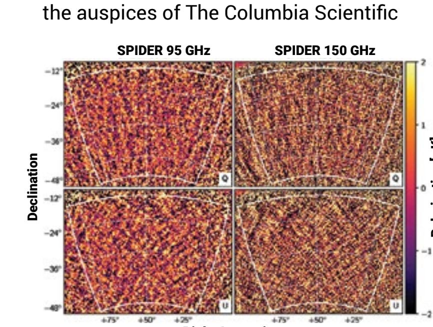


A microscope image of a bolometer island and surrounding dipole antenna array.



A close-up image of the island, with both TES devices and the meandering gold resistor clearly visible.

The first light emitted after the Big Bang approximately 14 billion years ago can still be seen as the cosmic microwave background (CMB). By mapping the polarization of the millimeter wave across as much of the sky as possible, the Suborbital Polarimeter for Inflation, Dust, and the Epoch of Reionization (SPIDER) mission aimed to reveal fundamental characteristics of these primordial gravitational waves, leading to a much greater understanding of the processes by which the universe expands. SPIDER is led by William Jones, a Professor at Princeton University. He obtained funding from the NSF and NASA in 2010, but it was not until 2015 that the mission was launched. To gather the data, observations had to be made free from interference, well above the surface of the Earth. However, rather than being launched into space, SPIDER spent 16 days hanging from a giant helium balloon floating 115,000 feet (35 kilometers) above the Antarctic under the auspices of The Columbia Scientific Balloon Facility (CSBF), a NASA facility managed by Northrop Grumman. Very little data could be collected via satellite links, so the computers and drives needed to be physically recovered. However, SPIDER returned to Earth in a remote area where the nearest civilization was the British Antarctic Survey (BAS) Rothera Station, nearly 1,000 miles from the landing site but much closer than the NASA facility at McMurdo Station. The BAS assisted with the data recovery, providing a great example of international cooperation.

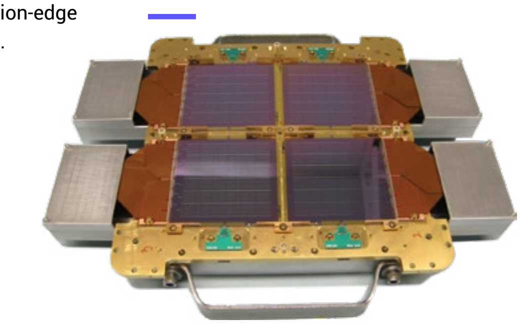


Q and U polarization maps in SPIDER's field.

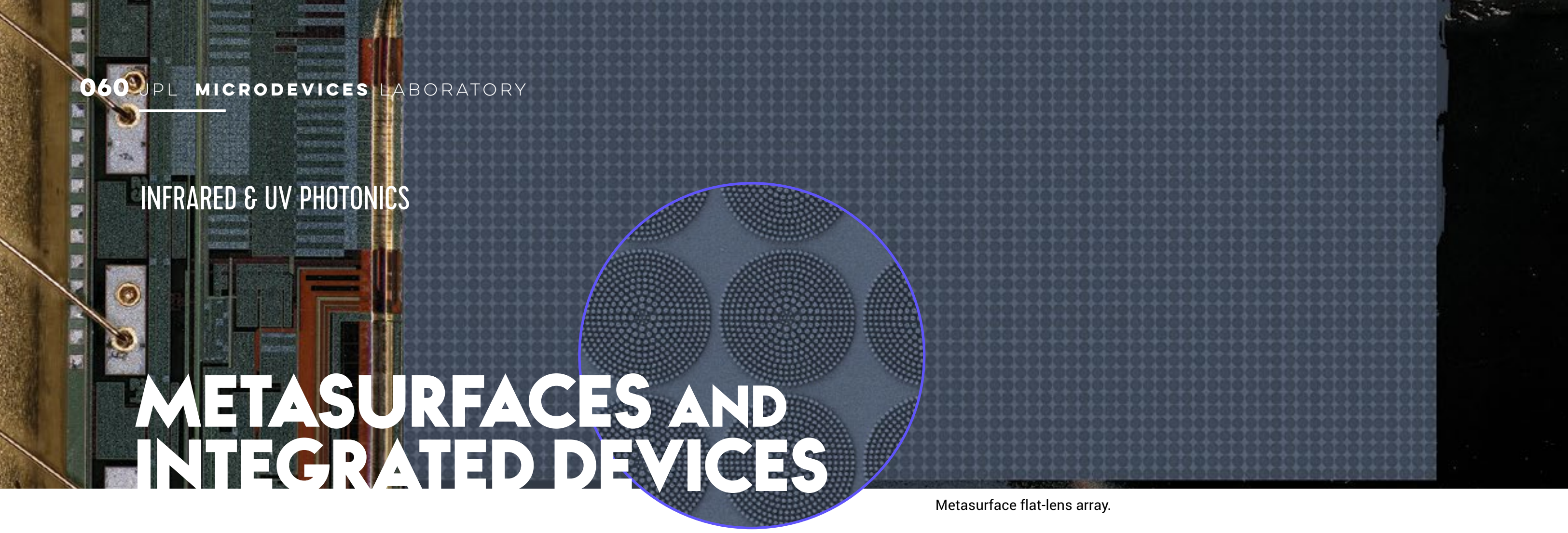
The SPIDER detectors had to provide the highest possible instantaneous sensitivities to CMB polarization. The SPIDER payload consisted of six monochromatic refracting telescopes in a single liquid helium cryostat, which was within a lightweight carbon fiber housing. Each telescope focused radiation onto four wafers ("tiles") of antenna-coupled transition-edge sensors fabricated at MDL.

Each wafer was patterned with an array of polarimeter pixels consisting of two inter-penetrating arrays of slot antennas (one for each perpendicular polarization mode). This arrangement provided for an instantaneous measurement of total intensity and one of two linear polarization components.

Since the data were retrieved, there has been an extensive effort to analyze the information and produce publishable conclusions. The data have built upon the results of the Planck mission and proven it possible to constrain some basic parameters for essential models. The results have been collected in a nearly completed paper to be submitted in 2021. Most importantly, both the technology and the results showed that the balloon approach is the most appropriate for this type of research; this result will help NASA prepare for any future satellite flight mission.



The underside of a fully populated SPIDER150 GHz focal plane during assembly, with the 8×8 grid of pixels visible on each of the four tiles.



INFRARED & UV PHOTONICS

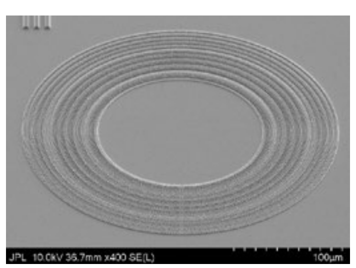
METASURFACES AND INTEGRATED DEVICES

Metasurface flat-lens array.

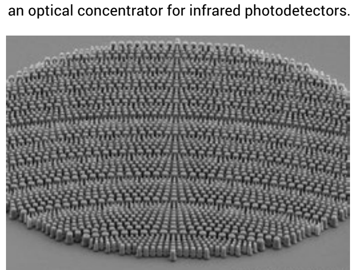
A GLIMPSE OF THE FUTURE

METASURFACE TECHNOLOGY FOR OPTICAL COMPONENTS

MDL is developing metasurface-based optical components that function by manipulating electromagnetic energy on subwavelength scales. This technology could lead to optical components with improved performance over existing technologies, as well as novel features.



SEM (scanning electron microscope) image of a fabricated metasurface annulus intended as an optical concentrator for infrared photodetectors.



SEM image of a fabricated off-axis metalens intended as an optical concentrator for infrared photodetectors.

METASURFACES

A metasurface is a surface containing features that are small relative to the wavelength the metasurface affects. Recent developments in metasurfaces based on geometric properties have led to the possibility of a revolutionary new class of optical components. Such metasurfaces enable the redesign of optical components into thin, planar and multifunctional elements, promising a major reduction in size and system complexity, as well as the introduction of new optical functions. Metasurfaces comprise sub-wavelength-scale structures whose optical properties are mainly determined by their geometric parameters rather than by material composition. By properly designing metasurface structures, it is possible to control the amplitude, phase, and polarization of incident light simultaneously in a compact manner. This unique capability of metasurfaces often allows them to combine the functions of multiple conventional optical components into a single device. Moreover, the manufacturing of metasurfaces is based on lithography, the same technology used for the manufacturing of computer chips, infrared detectors and focal plane arrays (FPAs). These properties, together with the flat configuration of metasurfaces, permit the cost-effective mass manufacturing and precise alignment of high-end metasurface components, a revolutionary advantage over conventional counterparts.

Metasurface-based components can enable instruments to spectrally decompose light from distant objects in novel ways. This spectral decomposition can enable researchers to detect the presence and abundance of chemicals such as water in order to classify land usage and map water stress on Earth, as well as measure pollutants in the atmosphere. Other applications for metasurfaces include optical imaging, laser detection, wavefront sensing, and coronagraphy. An interesting development is the use of metasurfaces for reducing the size and power requirements of existing instruments to make them compatible with small satellite mission where SWaP (Size, Weight, and Power consumption) is limited.

FLAT LENSES

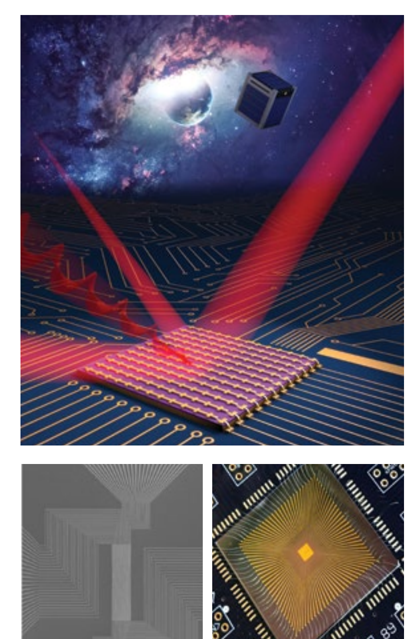
The prospect of planar, thin, optical lenses is very exciting, as it offers a major reduction in size and complexity. MDL has been developing metasurface-based flat lenses as optical concentrators that can be monolithically integrated with infrared photodetectors, FPAs, and other active and passive photonics devices. MDL has been pursuing these possibilities in collaboration with the Capasso Group and the Center for Nanoscale Systems at Harvard University. The optical concentrators enable an increase in the optical collection area of photodetectors that increases their detectivity and operation temperatures, thus reducing their cooling needs. This integration enables highly compact infrared instruments for space applications, especially where size and power are limited.

The NASA Center Innovation Fund provided the initial startup support for this initiative. NASA's Earth Science Technology Office (ESTO) has funded work on flat metalenses through the Advanced Component Technology (ACT) program. We will seek additional funding to develop this technology further. This funding may come from the NASA ACT program, NASA's Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program, or the JPL Topical Research & Technology Development (RTD) program, as well as from reimbursable sponsors such as DARPA and the Army, among others.

METASURFACE FILTERS INTEGRATED WITH FLAT LENSES FOR INFRARED FOCAL PLANES

Metasurface-based optical filters can be directly integrated with pixels in an FPA to create highly compact multispectral imagers. In addition, the use of planar metasurface-based concentrators enables the stacking of both filter and concentrator directly onto the detector array. This strategy will enable highly compact multispectral imagers capable of operating with reduced cooling.

The most recent work has shown the feasibility of this approach with the first metasurface resonant cavity long-wave infrared FPA. This development was supported by the NASA ESTO ACT program.

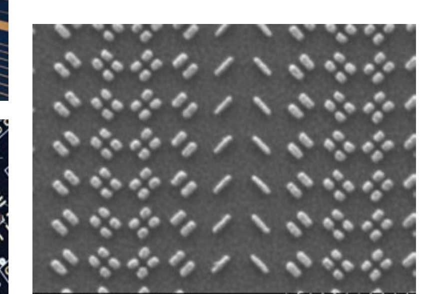


Multifunctional electro-optically tunable metasurfaces are capable of providing multiple functions such as beam steering and focusing using a single chip device. Such low SwaP metasurfaces enable system integration, especially for small satellite missions where size, mass, and power are limited.

METASURFACE IMAGING SPECTROPOLARIMETRY

Pollutants in the part of the atmosphere nearest the surface of the Earth, as well as in the middle to upper troposphere, have very significant effects on the surface environment and on local and global climate. Consequently, there is a need to develop a satellite observing system, preferably in a CubeSat format to reduce costs. In support of this need, NASA ESTO has funded a major project to develop the capability to observe and measure these pollutants. Dejian Fu in the JPL Science Division received an award to produce "A broadband metasurface for high spectral resolution, imaging spectropolarimetry," a key technology to enable the mission.

The instrument, the High-resolution Multispecies Atmospheric Profiler (HiMAP), is being developed at MDL with a metasurface designed by Prof. Hui-Hsin Hsiao's group (National Taiwan Normal University) and will resolve incoming light into four spectrally dispersed polarization components. The MDL E-Beam Technologies Group has designed and fabricated the optical system, which gives four spectropolarimetric images on an FPA, allowing simultaneous radiometric analysis.



30 nm E-beam lithography to enable a novel imaging spectropolarimeter, HiMAP.

INTEGRATED PHOTONICS

Electro-optically tunable metasurfaces are a class of metasurfaces that can be reconfigured after they have been fabricated. This flexibility offers the possibility of previously unimaginable optical capabilities with greatly enhanced performance and resolution. This exciting concept has been pursued by MDL NEXT postdoc Kafaie Shirmanesh. She is also researching photonic devices to couple light from a telescope into a multichannel integrated photonic circuit (PIC) and from the PIC out to a detector. Such devices will be the key components in astrophotonic applications such as chip-based spectrographs, coronagraphs, and programmable optical elements. In addition, she is working on the demonstration of an ultracompact metasurface-based spectropolarimeter in the ultraviolet (UV) range that can spatially decompose different polarization states and wavelengths.

FUTURE MISSION PROSPECTS

Other possibilities for the future include integrated filters that can be used to create highly rugged miniature single-pixel spectrometers for *in situ* applications. Such spectrometers could be used on microprobes deployable from orbit around a planetary body. Microprobes have previously been considered for penetrating the top surface of planetary bodies to study the composition and characteristics of the soil under the immediate surface. These components include water content in the subsurface, as well as the presence of other chemicals.

A probe dropped from orbit would be subjected to considerable g-forces upon impact, and to survive, it has to be highly ruggedized. Metasurface filters directly integrated onto the detector pixel itself provide a means of creating a highly rugged single-pixel spectrometer without the use of any post-fabrication alignment structures that might fail on impact. Such an instrument concept provides a revolutionary approach for future low-cost microprobes deployable from orbit.

ADVANCED OPTICAL & ELECTRO-MECHANICAL MICROSYSTEMS

MICROVALVES

CONTROLLING GAS FLOW IN AN AIR QUALITY MONITOR

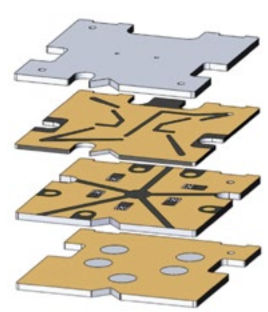
The Spacecraft Atmosphere Monitor (S.A.M.) is a miniaturized gas chromatograph mass spectrometer (GC/MS) on the International Space Station (ISS). It continuously monitors the major constituents and trace organic volatiles in the cabin air. It works in two modes: continuously sampling the major constituents of the air through a leak, or undertaking trace gas analysis (TGA). TGA involves manipulating the sample to and through a pre-concentrator GC to the same analytical device used for both modes, a quadrupole ion trap MS. Sample handling for TGA involves a number of microvalves (MVs); however, previously attempted on/off MVs have suffered from various issues, including stiction, which resulted in the valves being permanently stuck in an open or closed position. To mitigate these issues, an all-silicon, normally open pressure-balanced MV is currently being developed.

EXCELLENT AIR QUALITY IN THE ISS IS ESSENTIAL FOR CREW HEALTH, AND AN MDL-DEVELOPED INSTRUMENT BREATHES AND TESTS THAT AIR

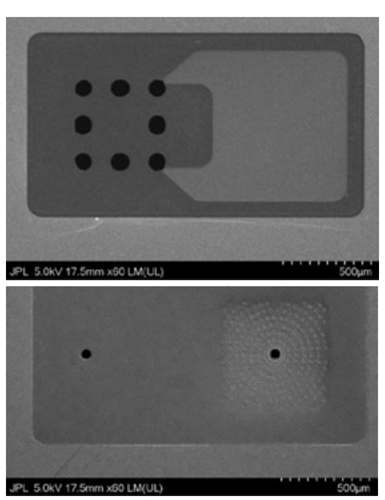
The MV is essentially an electrostatic parallel plate actuator. A moveable plate (membrane) is fabricated on a silicon-on-isolator (SOI) wafer, and a stationary plate hosting a gas inlet and a gas outlet is implemented on a separate SOI wafer. Both of these SOI wafers are highly doped. Two additional regular silicon wafers complete the MV, with the top wafer holding the gas channels and the bottom wafer providing sealing. All four wafers are then bonded via gold-to-gold thermocompression, where the initial gap between the membrane and the stationary plate is defined by adjusting the thickness of the gold layers.

The latest design iteration of the MV implements some important key changes. It has five independent membranes that are electrically isolated from one another; this arrangement fully controls the gas flow going to each port and suppresses crosstalk. To address the potential membrane stiction issue, additional design changes have been implemented. Compared to past generations, the membrane is designed to be substantially stiffer in the out-of-plane direction, enabling a very high restoring force while keeping the pull-in voltage and maximum stress at reasonable levels. On the other hand, the stationary plate design features a circular array of pillars, which significantly reduces the contact area during pull-in and therefore minimizes adhesion forces.

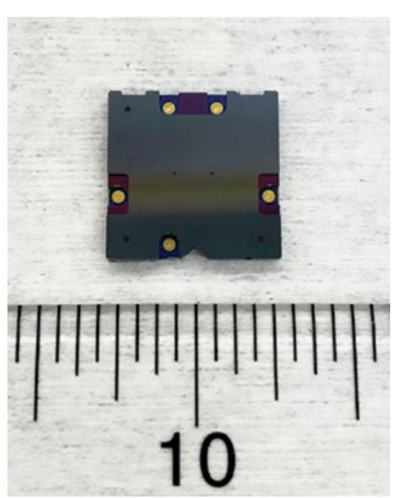
With the aforementioned key changes implemented, qualification tests have been conducted on the fabricated devices. The results have shown that the latest MVs, entirely fabricated at MDL, have excellent electrical isolation and can perform at least hundreds of on/off cycles without stiction or fatigue failure. When tested in experimental scenarios simulating flight-like operation configurations, they offer acceptable levels of leakage, even without the use of an on-chip sealing material such as epoxy. While this technology offers a solution to a specific problem, the development of these components will surely find many more uses in other devices in the future.



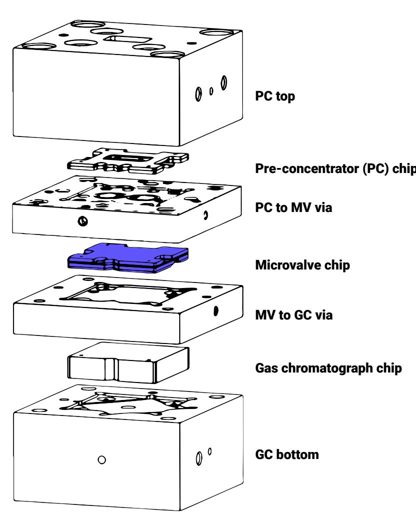
The microvalve is composed of 4 silicon layers, all gold coated for Au-Au thermocompression bonding.



Scanning acoustic microscope images of the membrane and the stationary plate.



An image of a microvalve fabricated at MDL (mm ruler scale).



Multiple microelectromechanical system components, all fabricated at MDL, will be integrated with the S.A.M. instrument.

APPENDICES

Peer-Reviewed Journal Publications

1. Abeywickrama, C., Premaratne, M., Gunapala, S.D., Andrews, D.L. Impact of a charged neighboring particle on Förster resonance energy transfer (FRET). Journal of Physics Condensed Matter, Vol. 32, Art. no. 095305 (2020). DOI: 10.1088/1361–648X/ab577a
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Conference Publications

1. Belousov, A.; Miller, M.; Continetti, R.; Madzunkov, S.; Simcic, J.; Nikolic, D.; Malaska, M.; Hodyss, R.; Waller, S.; Lambert, J.; Jaramillo-Botero, A.; Maiwald, F.; Cable, M., "Laboratory Simulations of Enceladus Plume for Fly-By Mass Spectrometery Validation", 51st Lunar and Planetary Science Conference, held 16-20 March, 2020 at The Woodlands, Texas. LPI Contribution No. 2326, 2020, id.1597 poster 51th LPSC; https://www.hou.usra.edu/meetings/lpsc2020/eposter/1597.pdf

2. Chattopadhyay G. Space Science and Instruments at NASA. 42nd Annual Symposium of the Antenna Measurement Techniques Association (AMTA 2020 - Virtual), November 2020. https://amta2020.org/wp-content/uploads/AMTA-2020-Final-Program-10-26_Updated.pdf Invited Address.

3. Gonzalez, M.P., Lopez, V., Winiberg, F., Christensen L., Noell, A., Kidd, R.D., Homer, M. L., Fridosy, S., Jewel, A., Darrach, M., Morrison, C., & Callahan, M., "Photocatalytic Oxidation Using TiO2 and UV for Total Organic Carbon Analyses of Water," Proceedings 50th International Conference on Environmental Systems, Lisbon, Portugal, ICES-2020-67. https://ttu-ir.tdl.org/bitstream/handle/2346/86251/ICES-2020-67.pdf?sequence=1

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Awards and Recognition by External Organizations

1. Alan Kleinsasser was named a Fellow of the IEEE effective January 1, 2021.

Book Contributions

None

New Technology Reports

1. Ferreira Santos, M.S.; Noell, A.C; Metz, B.C. Radiation Tolerant Capacitively Coupled Contactless Conductivity Detector (C4D), NTR# 51458 (2020).

2. Gonzalez, M.P., Noell, A., Jewel, April, Winiberg, F., Christensen, L., Homer, M.L., Darrach, M.R., Kidd, R.D., Fridosy, S., Valeria, V., Morrison, C. Photocatalytic Oxidation Using TiO2 and UV for Total Organic Carbon Analysis of Water. NTR# 51849 (2020).

3. Kehl F., Demartino A. J., Drevinskas T. (2020), High Voltage Liquid Flow Sensor, NTR # 51680

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7. Soibel, A. et al. Large metasurface-based optical concentrators utilizing a modular design, NTR 51912 (2020)

8. Soibel, A. et al. Metamaterial-based spectral filters and polarizers for compact spectrometers and polarimeters. NTR 51535 (2020)

9. Toda, R., Kidd, R.D., Gonzalez, M.P., Bae, B., Coskun, M.B., Shevade, A., Manohara, H. Robust Microvalve with External Actuation. NTR# 51670 (2020).

Patents

1. Chattopadhyay G., I. Mehdi, C. Lee. J. J. Gill, C. Jung-Kubiak, and N. Llombart, "Method for Making Antenna Array" US 10,693,210 B2 June 23, 2020.

2. Drevinskas T. Electrospray Compartment for Capillary Electrophoresis-Mass Spectrometry. CIT File No.: CIT-8610-P. Filed: 3/5/2021

3. Drevinskas T., Kehl F., Zamuruyev K. Closed High Voltage Compartment with High Surface Area Electrode for Capillary Electrophoresis. CIT File No.: CIT-8630-P. Filed: 4/8/2021

4. Kehl F., Demartino A. J., Drevinskas T. High Voltage Liquid Flow Sensor. CIT File No.: CIT-8518-P. Filed: 9/3/2020

5. Ting, D. Z., Soibel, A., Khoshakhlagh A., Gunapala S. D. Enhanced quantum efficiency barrier infrared detectors. U. S. Patent No. 10,872,987 B2, December 22, 2020.

2020 MDL Equipment Complement

Material Deposition

- Electron-Beam Evaporators (7)
- Thermal Evaporators (5)
- 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 with X20 PLC upgrade.
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Beneq TFS-200 Atomic Layer Deposition (ALD) System
- Custom integrated Atomic Layer Deposition and Metal Evaporation system
- Tystar (150-mm/6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 3 Tubes for
  - » Low-Stress Silicon Nitride
  - » Atmospheric Wet/Dry Oxidation
  - » Oxy-Nitride growths
- 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) with computer upgrades
  - » Veeco Epi GEN III MBE (III-V Antimonide Materials)
  - » Veeco GENxcel MBE (III-V 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
- Heidelberg MLA 150 Maskless Aligner with 375nm, 405nm, and Gray scale modes (1.0-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
- Sonotek Exacta Coat E1027 Photoresist Spray Coater
- Ovens, Hotplates, Furnaces, and Manual Spinners (4)

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)
- SPTS Omega LPX Rapier 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 (6), including (1) dedicated for batch processing of 6" wafers
- S-cubed Spray Liftoff and Photoresist removal tool
- Rinser/Dryers for Wafers including Semitool 870S Dual Spin Rinser Dryer
- Chemical Hoods (7)
- Acid Wet Processing Benches (7)
- Jelight UVO-Cleaners (2)
- Novascan UV8 Ultraviolet Light Ozone Cleaner
- Tousimis 915B Critical Point Dryer
- Solaris 150 Rapid Thermal Processor
- Polishing and Planarization Stations (4)
- 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
- 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 XT 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
- Jandel Model RM3000+ 4-Point Probe System
- 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 Atomic Force Microscope (AFM)
- KLA-Tencor Surfscan 6200 Surface Analysis System Wafer Particle Monitor with upgraded Software
- Hitachi Regulus 8230 UHR Cold Field Emission Scanning Electron Microscope (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)
- VEECO / WYKO NT 9300 Surface Profiler (including 50X optics)
- Zygo ZeMapper non-contact 3D Profile
- Thermo Scientific LCQ Fleet CE / MS (Capillary Electrophoresis / Mass Spectrometer) System
- Lakeshore Cryotronics Model CPX 1.7 Kelvin Cryo Probe Station

The Visiting Committee, September 5-6, 2019

MDL VISITING COMMITTEE

Meeting every two years to review the ongoing work at MDL and make valuable suggestions for future directions, the MDL Visiting Committee 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 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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Former JPL Chief Technologist, former Director of JPL's Microdevices Laboratory, and Merle Kingsley Professor of Physics, California Institute of Technology

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Cover: We are going back to the Moon, and MDL is helping. Lunar ice and soil may be used to produce oxygen propellant, but the oxygen must not contain any water. The LIRA sensor can check gas streams continuously and detect water at one part per million. This MDL technology, developed originally for *in situ* analysis on Mars, uses the absorption of long-path-length laser light for sensitive analyses (front cover). Inventions at MDL are developed and imaginatively reapplied to inform instrument designs, allowing us to rise to future challenges as they appear.