National Aeronautics and
Space Administration

30 YEAR ANNIVERSARY

3 DECADES OF INNOVATION FOR NASA

MICRODEVICES LABORATORY
2020 ANNUAL REPORT

Jet Propulsion Laboratory

1991
NASA's Upper Atmosphere Research Satellite (UARS) and JPL's Microwave Limb Sounder (MLS): first proof of chlorine monoxide destroying ozone.

1995
Kuiper Airborne Observatory (KAO): heterodyne receivers; first detection of interstellar space molecular water.

1996
The High Altitude Ozone Measuring and Educational Rocket: advanced delta-doped CCD to measure ozone concentration in Earth's upper atmosphere.

1997, 1998 & 2003
Balloon Observations of Millimetric Extragalactic Radiation and Geophysics (BOOMERANG): bolometers measured CMB to show the Universe is "flat."

2004
Rosetta Orbiter: Microwave Instrument (MIRO); measured gases from comet Churyumov-Gerasimenko, the first microwave device in space to study a solar system body.

2004
Earth Observing System (EOS) Microwave Limb Sounder (MLS): first THz heterodyne radiometer in space; measured stratospheric molecules, with radiometers & other devices.

2001
Genesis Mission: MDL coated and shape verified >25% of the solar wind collector arrays; to understand the evolution of the solar nebula over the last 4.6 billion years.

2005
Mars Reconnaissance Orbiter (MRO), Compact Reconnaissance Imaging Spectrometer for Mars (CRISM): curved gratings; defined Gale Crater landing site.

2005
Mars Reconnaissance Orbiter (MRO), Mars Climate Sounder: uncooled IR thermopile detectors for Mars atmosphere analysis.

2008
Chandrayaan-1, Moon Mineralogy Mapper (M3): curved gratings for the imaging spectrometer; first signs of surficial water in the moon's sunlit area.

2009
Herschel Space Observatory, Spectral and Photometric Imaging Receiver (SPIRE): enabling detectors; found distant infrared-luminous galaxies.

2009
Herschel Space Observatory, HIFI (extremely high-resolution far-Infrared heterodyne spectrometer): enabling detectors; found water vapor on Ceres in the asteroid belt.

2009
LRO (Lunar Reconnaissance Orbiter), Diviner Lunar Radiometer Experiment: thermopile detectors; identified places that could preserve ice for billions of years.

2009
TacSat-3 spacecraft's primary payload, the Advanced Responsive Tactically-Effective Military Imaging Spectrometer, or ARTEMIS, with MDL fabricated gratings delivers processed information to the warfighter on the ground within 10 minutes, following a single-pass collection opportunity on a specified target.

1990 | 2000 | 2005 | 2010 | 2015 | 2020

1995
Space Shuttle: Signature Chips fabricated, packaged, delivered and flown: Public outreach.

2000
Earth Observing 1 (EO-1): Hyperion high resolution hyper-spectral imager; E-beam grating; technology validation mission.

2000
Space Technology Research Vehicle (STRV-1D): Quantum Well Infrared Photodetector (QWIP) focal plane array; testing new technologies in orbit.

2003-2008
Black Brant IX Sounding Rocket, Johns Hopkins U.: delta-doped CCD in the Long-Slit Imaging Dual Order Spectrograph (LIDOS) on three missions.

2007
Phoenix Mars Lander, MECA (Microscopy Electrochemistry, and Conductivity Analyzer): technologies for soil sample analysis.

2009
Planck, HIFI (extremely high-resolution far-Infrared heterodyne spectrometer): detectors; enabled high precision photometry and polarimetry of the CMB.

2009
SOFIA (Stratospheric Observatory for Far Infrared Astronomy): heterodyne receiver; mapped/detected interstellar molecules.

2011
Mars Science Laboratory, SAM, Tunable Laser Spectrometer (TLS): tunable diode lasers; detailed methane on Mars.

2010
Carnegie Airborne Observatory (CAO) and National Ecological Observatory Network (NEON) received MDL fabricated micromachined slits and e-beam fabricated triple-blaze convex gratings for instruments to address a need for macroscale measurements that reveal the structural, functional and organismic composition of Earth's ecosystems.

2012-2014+
AVIRIS-NG & HyTES: curved diffraction gratings); terrestrial ecology observations.

AVIRIS-NG & HyTES: Quantum Well Infrared Photodetector (QWIP) Focal Plane Arrays (FPAs); terrestrial ecology observations.

2012
MICA (Magnetosphere Ionosphere Coupling in the Alfvén Resonator) Sounding rocket, to study aurorae: low voltage delta-doped CCD array for auroral electron detectors.

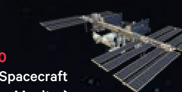
2018
2018 EUCLID, IR telescope: Spectral and Photometric Imaging Receiver (SPIRE) and silicon fan out boards for the ASIC; looking back to the earliest moments of our universe, investigating Dark Energy.

2018
Spacecraft Fire Experiment (Saffire): Combustion Product Monitor (CPM) instrument, measure specific fire products for astronaut safety.

2018
EMIT (Earth Surface Mineral Dust Source Investigation), ISS: imaging spectroscopy instrument, measuring mineral compositions of Earth's dust sources for climate prediction.

2018
Mars 2020, PIXL: diffractive spot array generators, 2-D computer-generated hologram (CGH) gratings, X-Ray maps of Martian rock chemistry.

2018
Mars 2020, SHERLOC: gratings for the Raman and fluorescence spectrometers; looking at Martian organics and minerals.



2018
WFirst (Wide-Field Infrared Survey Telescope), Hybrid-Lyot Coronagraph: pupil-plane mask; directly image and characterize exoplanets and debris disks in star systems.

2019 - 2020
ISS: SAM (Spacecraft Atmosphere Monitor): next generation gas chromatograph — mass spectrometer; astronaut health and safety.

2019 - 2020
SISTINE (Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet): Secondary mirror over-coated for unmatched UV reflectivity; to validate biosignature observations.

2019
TIME (the Tomographic Ionized Carbon Intensity Mapping Experiment) is the first instrument for spectral imaging array to investigate the early history of the universe.

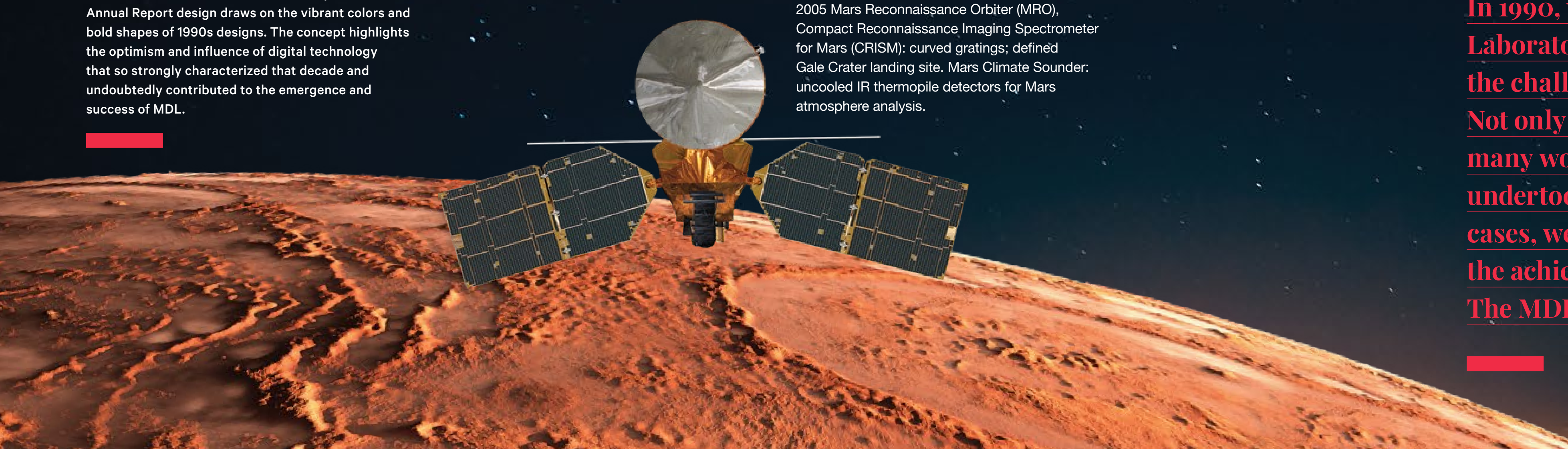
2020
Mars 2020, Perseverance Mars rover, Send Your Name to Mars campaign; 10,932,295 names on three silicon chips, Public outreach.

2010-2012
Balloon-borne Large Aperture Submillimeter Telescope (BLASTPol): 3 arrays of 280 bolometric 250, 350, & 500 µm detectors; galaxies producing the FIR/submm background .

2012-2016
BICEP, BICEP2 & BICEP3, Antarctic telescopes for CMB polarization: TES polarization bolometers; testing for early universe cosmic variance.

2014
SPIDER, balloon-borne experiment for CMB polarization: filters, antenna components, TES Arrays; seeking primordial gravity waves.

2017
Stratospheric Terahertz Observatory (STO-2), balloon-borne radio-telescope; room-temperature, multi-pixel, frequency-multiplied local oscillator: Life Cycle of Interstellar Medium.



2018
PREFIRE (Polar Radiant Energy in the Far Infrared Experiment), first cubesat IR and far-IR measurements of Earth's atmosphere from space: fully custom thermopile detector array.

2018
Psyche: Deep Space Optical Communications (DSOC): Superconducting nanowire single photon detectors (SNSPDs); improve communications performance 10 to 100 times.

2019
Europa Clipper, Mapping Imaging Spectrometer for Europa (MISE): slits and grating with a custom groove profile tailored to permit a single focal to be used; looking for ocean habitability.

2019
BICEP Array (Background Imaging of Cosmic Extragalactic Polarization): TES focal plane; Antarctic telescopes testing for early universe cosmic variability.

2020
Office of Naval Research Milliwave Telescope: focal plane of aluminum KIDs fabricated on crystalline silicon tiles; mm wavelength imaging when visible observation is obscured.

2020
30th anniversary of successful operations and deliveries from the Microdevices Laboratory (MDL).

30 years for NASA

MDL – A STORY OF CONTINUOUS ACHIEVEMENT

In 1990, within a year of its opening, the Microdevices Laboratory (MDL) was producing innovative solutions to the challenges presented by NASA mission requirements. Not only did MDL meet these immediate demands, but its many world-class scientists, engineers and technicians also undertook research to develop new approaches that, in many cases, were disruptive technologies. These advances enabled the achievement of previously unattainable scientific goals. The MDL staff continues this legacy today.

In celebration of MDL's 30th anniversary, the 2020 Annual Report design draws on the vibrant colors and bold shapes of 1990s designs. The concept highlights the optimism and influence of digital technology that so strongly characterized that decade and undoubtedly contributed to the emergence and success of MDL.

2005 Mars Reconnaissance Orbiter (MRO), Compact Reconnaissance Imaging Spectrometer for Mars (CRISM): curved gratings; defined Gale Crater landing site. Mars Climate Sounder: uncooled IR thermopile detectors for Mars atmosphere analysis.

The Orion nebula is a close neighbor in our Milky Way galaxy, only 1,500 light-years from Earth.

MDL HAS BEEN A KEY PLAYER IN JPL'S EFFORTS TO CREATE AND DELIVER HIGH-RISK, HIGH-PAYOFF TECHNOLOGY FOR NASA'S FUTURE PLANETARY, ASTROPHYSICS, AND EARTH SCIENCE MISSIONS, AS WELL AS NASA'S OTHER STRATEGIC NEEDS.

ORIGIN

Beginning the great venture

Although visionary, the leaders responsible for the origin of the Microdevices Laboratory (MDL) could not have imagined how it would go on developing from strength to strength in the succeeding 30 years.

Lew Allen, Jr. | Terry Cole | Carl Kukkonen

MDL came into existence in April 1990, and in April 2020, we celebrated its 30th anniversary. Although the COVID-19 pandemic meant that the celebration was virtual, it was nonetheless enthusiastic. The technology has changed in 30 years, but the ethos and the ability to produce unexpected, innovative technology has stayed the same. This milestone anniversary is a suitable time to look back at the history of MDL, understand how its values have been perpetuated to the present and envision how they will continue into the future.

Originally, MDL was a new laboratory facility, the jewel in the crown of the Center for Space Microelectronic Technology (CSMT), a JPL Center of Excellence. The CSMT arose from discussions in the early 1980s between the Caltech Board of Trustees and NASA to identify an emerging area in which JPL could take the lead for NASA. JPL already had expertise through the Advanced Microelectronics Program, established in 1983 at NASA's request. Dr. Lew Allen, the JPL Director, asked his chief technologist, Dr. Terry Cole, to organize this new effort. Dr. Cole envisioned a multidisciplinary approach to investigate many areas and produce a range of products, including microelectronic devices. To produce such devices, new cleanroom facilities and state-of-the-art equipment were needed; thus arose the need for a new laboratory for the embryonic CSMT. Dr. Cole's ambitious but realistic vision paved the way for future success. At this stage, Dr. Carl Kukkonen, who already had a distinguished career at the Ford Motor Company, was brought in as CSMT Director. Dr. Kukkonen was an able leader and was awarded the NASA Exceptional Achievement Medal in 1992.

A major change occurred in 2007, when MDL's dispersed parts were first brought together into a single organization centered on its unique laboratory facility. Its first director was Dr. Jonas Zmuidzinas. Thus, MDL's 30-year history of success resulted from its nurturing by Drs. Cole and Kukkonen, its subsequent stewardship by MDL directors and deputy director, and strong support from JPL directors.

In January 1987, the construction of the new NASA-funded MDL building was started. [left-right] Marvin Goldberger, Caltech president (1978-1987); Lew Allen, JPL Director (1982–1990); Burton Edelson, NASA's Associate Administrator for Space Sciences; and General Billie J. McGarvey, NASA's Facilities Engineering Division Director.

MDL HAS MADE SEMINAL CONTRIBUTIONS AS A RESULT OF THE DEDICATION AND HARD WORK OF MANY TALENTED SCIENTISTS, TECHNOLOGISTS, AND RESEARCH STAFF.

This is MDL

For the past 30 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**

MDL IS A JPL INSTITUTIONAL FACILITY CHARTERED TO CREATE, DEVELOP, DELIVER,AND INTEGRATE NOVEL MICRODEVICES AND CRITICAL MICRO DEVICE TECHNOLOGIES TO ENABLE OR ENHANCE INSTRUMENTS AND MISSIONS THAT BENEFIT JPL AND NASA.

MDL's commitment

We are excited to celebrate the 30th anniversary of the Microdevices Laboratory at JPL and the many important contributions that MDL devices and technologies have made to NASA missions.

Operations began at MDL in the spring of 1990 with a vision to develop new microelectronic devices that were not available elsewhere. Over the next three decades, MDL exceeded all expectations, contributing broadly and deeply with original and enabling devices benefiting the full spectrum of NASA missions. These contributions included novel spider web bolometers for measuring cosmic radiation in the PLANCK mission, multi-octave gratings in the M3 instrument for detection of water compounds on the illuminated surface of the Moon, and the advanced tunable lasers of TLS for measuring methane on the surface of Mars.

More recently, MDL has contributed key optical components for astrophysics instruments on JWST and WFIRST, as well as for the PIXL and SHERLOC instruments on the Mars Perseverance rover. An innovative calibration target was developed for ECOSTRESS and enabling devices are being developed for the EMIT and PREFIRE Earth missions. MDL is fabricating single photon counting detectors for the Deep Space Optical Communication demonstration, as well as elements of the Combustion Product Monitor to benefit human space flight missions.

Within MDL, we are also developing new technologies for in situ life detection, chemical analysis in space, and working to develop a range of new device types for NASA. MDL embodies the Laboratory's pioneering spirit and unique blend of scientific and engineering talent. I invite you to learn more about MDL's exceptional three-decade legacy.

MIKE WATKINS
Director, Jet Propulsion Laboratory

This year, we celebrate the 30th anniversary of MDL and its many extraordinary contributions and achievements. This year has also been unprecedented and challenging with the arrival of the COVID-19 pandemic. MDL, along with much of JPL, was shut down in March. However, as evidence of its importance to NASA missions, MDL was restarted in early May with a rigorous set of new safe to work procedures and processes to facilitate critical flight mission device development. We are now advancing to deliver these devices for our customers.

Over the past three decades, MDL has fulfilled its commitment to invent, develop, and deliver novel microdevices and critical microdevice technologies that enable new capabilities, instruments, and missions for NASA. The key to this success is best exemplified by the picture on page 4, taken at the February all-hands meeting: this community of scientists, technologists, and other professionals is the driving force behind MDL. The group is committed to supporting the JPL Directorates to develop and deliver the devices needed for a broad set of current and near-term NASA missions. In parallel with fulfilling current commitments, MDL is investing in new ideas, technologies, and research to enable the next generation of novel devices for NASA. These future investments are guided by the biannual Visiting Committee review, the Directorates' needs, and interactions with universities and other advanced technology laboratories.

Within this annual report, you will learn more about the 30-year history of MDL, our current activities, and our investments for an exciting future filled with advanced devices and innovations for discovery and exploration.

ROBERT O. GREEN
Director, Microdevices Laboratory

MDL IS MAKING INVESTMENTS IN PEOPLE, EQUIPMENT, AND TECHNOLOGIES TO ENABLE NEW CLASSES OF DEVICES THAT WILL SUPPORT EXCEPTIONAL MISSIONS FOR NASA IN THE 2025 AND 2035 TIMEFRAMES.

Contents

MDL coronavirus challenge

When COVID-19 arrived, MDL was very well prepared. The lab survived the lockdown thanks to many valiant efforts, and recovery is already underway.

VITAL SUPPORT AGAINST COVID-19

PRIMARY

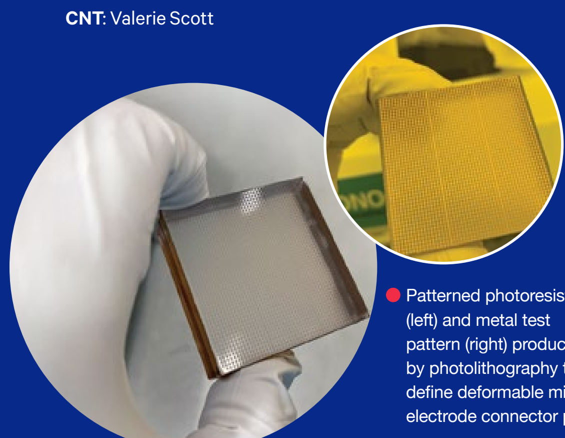
MDL Safety: James Lamb, Amy Posner, Mark Mandel
MDL Facilities: Ramzy Rizkallah
MDL Equipment: James Wishard, Rick Leduc

SECONDARY / CONTINGENCY

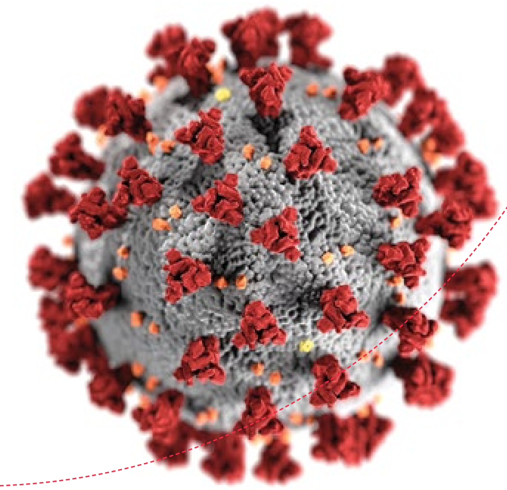
MDL Safety: Michael Martinez
MDL Facilities: Roopinderjit Bath, Toney Davis
MDL Equipment: Mike Fitzsimmons, Chuck Manning, Matt Dickie, Frank Greer, James Wishard—for most central processing equipment (RIEs and Deposition systems), Mike Fitzsimmons—steppers and spin developer systems, Matt Dickie—for DRIEs, LPCVD, SEMs, furnace systems, & RCA wet bench, Frank Greer—for ALDs (John Hennessy as back-up) precursor source shut-downs, and Black Si Cryo Etcher.

MDL TASK-SPECIFIC EQUIPMENT

EBeam: Dan Wilson, Rich Muller
III-V MBE: Cory Hill, Arezou Khoshakhlagh
Si MBE: April Jewell, Alex Carver
UHV Lesker: Rick Leduc, Bruce Bumble
FC300: Brian Pepper
CNT: Valerie Scott



Patterned photoresist (left) and metal test pattern (right) produced by photolithography to define deformable mirror electrode connector pads.



Although 2020 is a year of great celebration at MDL, we would be remiss if we did not acknowledge the effects of the COVID-19 pandemic. The virus' global reach also affected MDL, and it was likely the greatest challenge the JPL staff has collectively faced. We owe a monumental debt of gratitude to many people, including JPL senior management; the MDL staff, particularly the MDL Support Group; and especially the MDL team members who came in during the shutdown to check on the lab.

The senior management at JPL, ahead of any directives from NASA headquarters, made the safety of all staff their first priority and planned accordingly for as many as possible to work "Safer at Home." In line with this plan, the staff held a practice session for working remotely from home. The session included the first MDL User Forum/MMR held via WebEx. However, the situation changed very quickly as COVID-19 escalated in southern California. Less than a week later, and with only one day's notice, it was announced that from Tuesday, March 17, JPL would be moving to mandatory telework; therefore, live semiconductor processing would stop. JPL would be closed to all but approximately 10% of employees. Those allowed in were required for the Mars 2020 mission and could not work from home or were staff performing laboratory security and maintenance functions. Extreme care was taken to ensure the safety of personnel during the last day of work by shutting off cleanroom entry air showers and supplying liberal amounts of hand sanitizer to MDL scientists as they attempted to complete their devices. Completed devices could then be tested by collaborators in other states and countries—and sometimes even in the JPL staff members' own homes.

Once the cleanroom processing was safely and successfully complete, the MDL Support Group put MDL into a Safe Idle state, with many pieces of equipment left powered on. MDL is very safety oriented and would fail safe in the event of a disaster, but the Safe Idle state was preferable to a complete shutdown because many of the types of semiconductor processing equipment in MDL do not recover well from being powered off. For example, process exhaust pumps can have chemical byproduct residues that congeal when the pump cools down, resulting in the motor seizing up permanently. After a full shutdown, a month or more would be needed to return the cleanroom to a normal operating state. In going into Safe Idle state, a few additional steps were taken to reduce the amount of intervention required in the event of a disaster.

Some of the dozens of JPL engineers involved in creating the COVID-19 ventilator prototype.

First, all acutely hazardous gases were shut off at their source. Second, all chemicals that were in process were poured into waste containers. Finally, all ALD chemical precursors were shut off and isolated. This Safe Idle state was maintained via safe daily monitoring by three individuals on separate shifts (one person at a time on site) who checked facilities systems values versus setpoints, as well as the status of safety monitors.

The Safe Idle state was maintained successfully for 53 days. Some routine cleanroom maintenance activities were performed as long as they required only very few people who could be adequately socially distanced during the work. For example, during the idle period, the wet scrubber was serviced and some regulators were replaced.

On May 8, NASA headquarters granted permission for MDL to make a small, phased reopening. Given the critical timelines associated with the WFIRST Coronagraph Instrument project deliverables, MDL was permitted to have up to 6 people in the cleanroom at a time working on two specific tasks: fabrication of interconnects for the mission's deformable mirrors and fabrication of occulting mask designs for the instrument testbeds. It took only two business days of cleanroom restart activities (facilities, safety, and equipment) to go from Safe Idle to fully operational. Only one piece of equipment, a Dektak8 profilometer, did not survive the restart, a testament to the value of avoiding a full shutdown.

After the partial restart, processing in MDL was very successful, with nearly half of the equipment in full use. Several deformable mirror test articles were delivered to internal and external partners, and several coronagraph masks were provided to the testbeds. A lesson learned from this shutdown has been that MDL must plan for more than just facilities and equipment startup: the human element of restarting lab work after a two-month absence is also important. For example, fixtures and supplies must be unpacked, and the regular routine of loading and calibrating systems must be restored.

MDL's system operated extremely well in the face of the pandemic. The staff did a fantastic job under these unimaginable circumstances, finishing tasks rapidly to prepare for the shutdown. Approvals were obtained for specific staff to enter at specific times. The safety assurance maintenance staff still had to work, and they showed exemplary dedication. We especially acknowledge the MDL staff who came to the lab every day to check its status in standby mode, even as JPL was generally closed to all but 10% of the workforce. Overall, MDL weathered the unexpected impact of COVID-19 well, and from the viewpoint of early June, the lab looks forward confidently to increasing occupancy and returning to full capacity as soon as it is safe to do so.

MDL VENTILATOR CONTRIBUTION

MDL scientists and engineers specialize in building devices for spacecraft, but the COVID-19 pandemic shifted their focus sharply away from distant galaxies and toward intensive care units. With the country's clear, urgent need for ventilators, an MDL team came together to design and produce a prototype ventilator that could be manufactured and distributed quickly. In just 37 days, the team working on the Ventilator Intervention Technology Accessible Locally (VITAL) project designed, built, and tested a prototype ventilator specifically for COVID-19 patients. The ventilator can be readily built from parts that are already in the supply chain, and it can be easily modified to function in environments ranging from standard intensive care units to field hospitals. The FDA granted Emergency Use Authorization for VITAL on April 30 and authorized a modified version of the device on June 4. On May 29, NASA selected eight US manufacturers to begin mass-producing VITAL units, which will soon be helping patients in need.

One MDL technologist who contributed to VITAL from Day 1 was Florian Kehl, who was tapped for his background in sensors and for a unique experience in Switzerland working on horse and camel ventilators at the Swiss Center for Electronics and Microtechnology (CSEM). Horses, and, in the Middle East, camels, are very valuable animals, but when they are anesthetized or undergoing surgery, their large lungs often collapse. To solve this problem, CSEM built a ventilator that could provide the large volumes and pressures of air that horses and camels require.

Florian's experience, combined with his background in biomedical engineering, made him a natural fit for the VITAL Design and Production Teams. As part of these teams, he was responsible for selecting a high-flow pneumatic valve, as well as sensors for flow, barometric pressure, and oxygen. He was also involved with the production of an injection-molded part. One challenge in his role was to secure the supply chain, for unlike most MDL projects, the goal of VITAL was to build not one or two devices but rather tens of thousands. Additionally, the device could not conflict with the medical market.

The VITAL team included several foreign nationals, including Florian, reflecting the involvement and support of the entire world. Florian has always been proud to be part of MDL, but thanks to his involvement with VITAL, he has never been prouder.

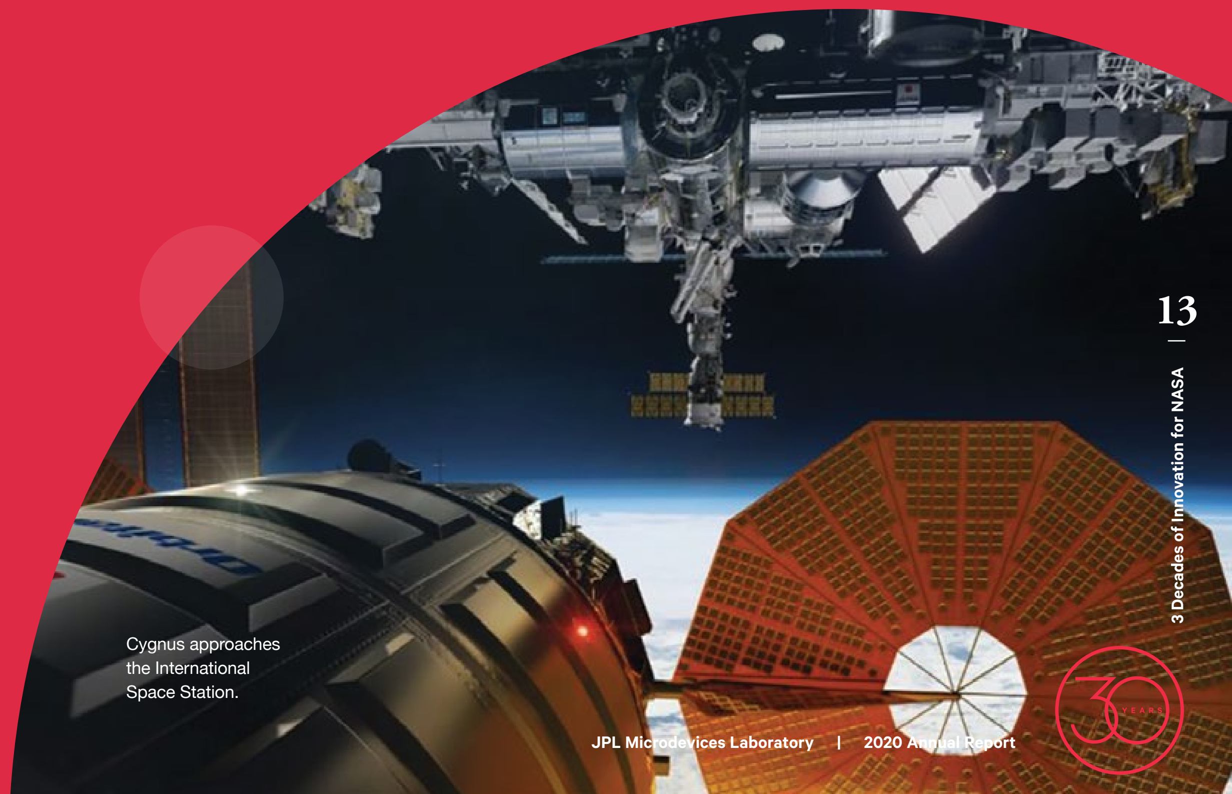
CATACLYSM

MEP thruster
being assembled.

MDL technologies preparing for the near future

The founders of MDL and its predecessor, the CSMT, foresaw the need for products, approaches, materials, and microdevices whose performance could dramatically outstrip the state of the art at any time. Developments aimed at fulfilling that demand continue.

The various projects in the current MDL portfolio have one thing in common: they are all examples of technology for spaceflight, aimed at helping NASA achieve successful outcomes in its missions and other significant scientific advances.



Cygnus approaches
the International
Space Station.

Send your name to Mars

Gaining immortality by traveling into space, albeit virtually, has changed perceptions of space exploration.

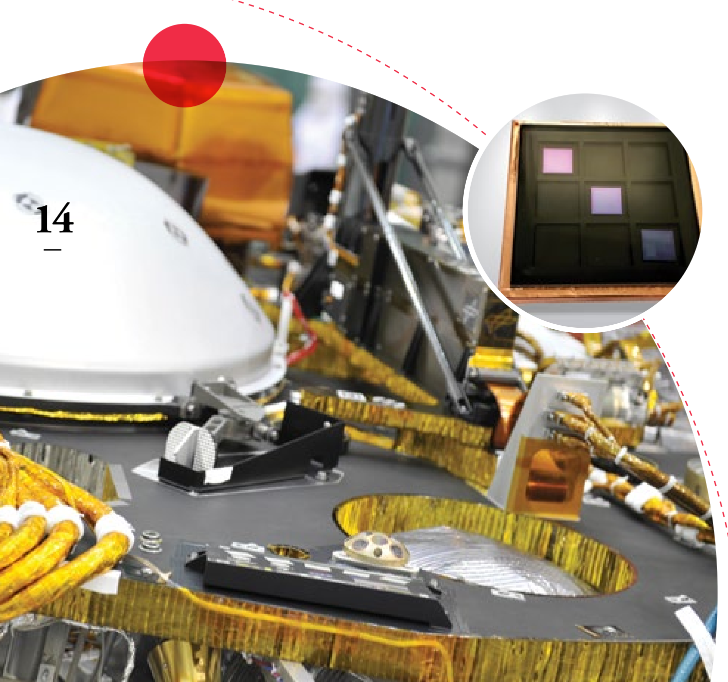
Brad Pitt shows off his "boarding pass" for Mars with Jennifer Trosper, the Mars 2020 project systems engineer.

A single chip is dwarfed by a scanning electron microscope (SEM) video image of the letters and boarding pass.

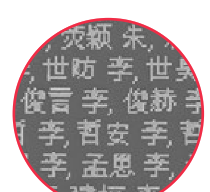
In keeping with a JPL tradition that started with the Star Dust spacecraft in the late 1990s and was continued by many other missions, MDL was asked to use its electron beam lithography capability to stencil millions of names submitted by the public onto silicon chips to generate excitement about and worldwide participation in the NASA's Mars 2020 Mission and its Perseverance Rover. Signing up for the "Send Your Name to Mars" web campaign, which opened on May 21, 2019, came with souvenir boarding passes and "frequent flier" points. This public engagement campaign aimed to highlight missions involved in NASA's journey from the Moon to Mars. Miles (or kilometers) were awarded for each "flight," with corresponding digital mission patches available for download. The Mars Public Engagement Team collected over 10.9 million names in every language. MDL's Electron Beam Fabrication Team was responsible for converting bitmaps into tiny readable text and using the electron beam system to stencil the submitted names onto three silicon chips. Using a deposition and lift-off process, they created lines of text 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 three fingernail-sized chips, affixed to the upper-left corner of the plate under a clear plastic cover, 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.

The work was funded by the NASA Mars Public Relations Office led by Carolina Carnalla-Martinez. MDL contributors were Pierre Echternach, Rich Muller, James Wishard, Matt Dickie and Chuck Manning.

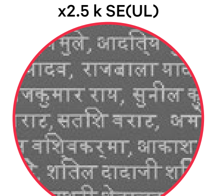


A plate was designed to include the 3 chips. Within the sun's rays is a message reading "explore as one" in Morse code.



8.2 mm x2.50 k
x2.5 k SE(UL)

SEM image examples of some of the millions of text characters which included over 100 modern and historic scripts.



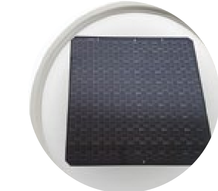
MDL used an electron beam to stencil the submitted names onto silicon chips. Three different chips were needed to fit all of the text (inset).

ONR telescope

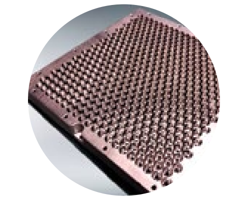
JPL and Caltech are developing a 3,840 detector, 140 GHz imaging camera paired with a 1.5 meter crossed Dragone telescope.

The Office of Naval Research (ONR), more than most users, wants to see clearly in adverse weather conditions, so they came to Caltech and JPL to improve their vision with MDL technology. For this terrestrial application, Kinetic Inductance Detector (KID) arrays enable passive imaging at millimeter wavelengths that penetrate optical obscurants such as fog. However, the same technology can be used to look farther afield: by allowing for larger-format, background-limited arrays, KIDs can improve an instrument's overall sensitivity for cosmic microwave background measurements.

The focal plane of the 1.5 m diameter ONR telescope is composed of aluminum KIDs fabricated on crystalline silicon tiles. The tiles contain 960 KIDs and are approximately 100 mm x 100 mm in size. KID pairs, each sensitive to an orthogonal linear polarization, are coupled to a waveguide/feedhorn machined from aluminum. A single block with 480 waveguides/feedhorns arranged in a hexagonal close-pack configuration is paired with each detector tile. Initial tests with prototype KID tiles showed the expected noise and optical performance. Full-scale tiles have now been fabricated with >90% yield and are currently being characterized. The imager is intended for terrestrial applications, and an initial demonstration with the ONR telescope was planned for early 2020. With relatively minor changes to the KID design, it could also be optimized for astronomical applications.



960-MKID detector array. The thin line meandering top to bottom over the entire array is the feedline used to read out the MKIDs.



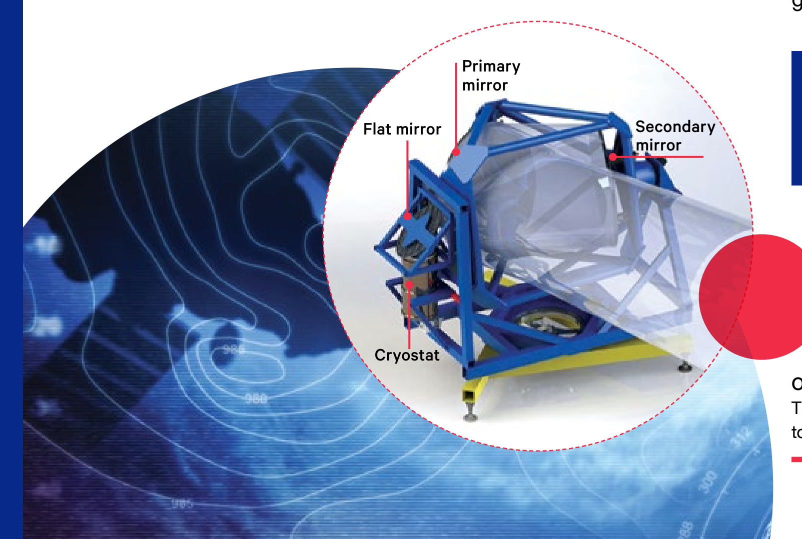
Horn array block. The 960 feed horns are drilled with a spline profiled drill bit to produce an array of wideband feedhorns.

Naval Research Lab produced the world's first space radio telescope in 1951, making the first radio detections from Mars, Venus, Jupiter, and Saturn (1956 – 1958).

In the full-scale 960-Microwave KID (MKID) Detector Array, the thin line winding from top to bottom over the entire array is the feedline used to read out the MKIDs. The horizontal "bands" represent the inter-digitated capacitor section of each MKID, with the size of the capacitor varied to produce resonant frequencies between 200 and 600 MHz. The inductive sections of the MKID, which are too thin to be seen in the photo, are located between each capacitor pair. A vertically oriented inductor couples to one capacitor, and a horizontally oriented inductor couples to the other capacitor, thus absorbing the incoming radiation in a polarization-selective way for each MKID. The image of the Horn array block shows the 960 feed horns drilled with a spline-profiled drill bit to produce an array of wideband feedhorns. Radiation incident on the feedhorn array is focused onto the detector array. Two MKIDs per feedhorn are used to detect orthogonal polarizations.

The use of the KID array allows for many more pixels than would be practically feasible with other detector technologies while achieving noise levels at fundamental limits. KIDS are relatively straightforward to manufacture, typically requiring few fabrication steps, and they are compatible with a readout multiplexing technique that allows for thousands of detectors to share a single readout channel, giving them an advantage in large arrays.

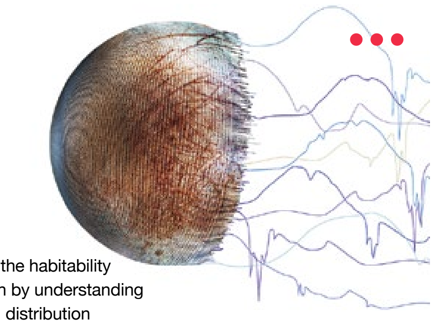
The MKID technology that enables the camera to function was originally developed by Peter Day and Rick Leduc at MDL in collaboration with Prof. Jonas Zmuidzinas at Caltech.



Overall schematic of the 140 GHz KID imager. The 1.5 m diameter primary mirror can be driven to point in any viewing direction.

Europa Clipper MISE

MISE is a near-infrared imaging spectrometer on board the Europa Clipper mission to Jupiter's moon Europa. It uses a diffraction grating and slit designed and fabricated at MDL. MISE will examine Europa's surface composition and relate it to the habitability of its ocean.



MISE will assess the habitability of Europa's ocean by understanding the inventory and distribution of surface compounds.

Europa has long been of astrobiological interest because it has a deep ocean and a thick surface layer of ice that appears to be constantly renewed from below and recycled into the ocean. The surface has areas that are rich in salts and contain complex organic compounds. These areas will be among the targets for investigation on the Europa Clipper mission, which is due to launch later this decade and will orbit Europa to assess whether it could support life. The spacecraft will perform 45 flybys of Europa at closest-approach altitudes of 1,700 miles to 16 miles (2,700 kilometers to 25 kilometers) above the surface. The Mapping Imaging Spectrometer for Europa (MISE) is one of nine instruments that NASA selected in 2015 for the mission. It will take images in reflected infrared light, and spectral analysis will produce maps of salts, organic matter and ices. The MISE spectrometer will operate at global (≤ 10 km), regional (≤ 300 m) and local (~ 25 m) scales.

MISE is being developed collaboratively by JPL and the Johns Hopkins University's Applied Physics Laboratory (APL). The instrument evolved from JPL's Discovery Moon Mineralogy Mapper (M3) on Chandrayan-1 and APL's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM).

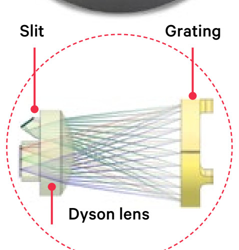
The instrument works at F/1.4 and covers a spectral range from 0.8 to 5 µm (near-infrared to mid-infrared). It has 10-nm spectral resolution, an instantaneous field of view of 250 µrad/pixel and a swath width of 300 active pixels. Mapping the composition of specific landforms is critical to understanding surface and subsurface geologic processes, including recent or current activity. The 3–5-µm spectral range is critical to detecting organics because weak C-C bonds (e.g., octane) in some aliphatic hydrocarbons contrast sharply with the stronger C=C (e.g., benzene) and C≡C bonds found in other hydrocarbons. These differences provide an approach to distinguish classes of hydrocarbons and to differentiate biological molecules from their abiotic equivalents.

The MISE high-optical-throughput, high-uniformity push-broom imaging spectrometer is enabled by MDL's electron beam lithography capabilities, which were used to shape MISE's gratings and slits. The MISE grating has a custom groove profile tailored to the MISE system's response through the entire spectral range, which permits a single focal plane array detector to be used. The precise slit produced by electron beam lithography is central to achieving MISE's uniformity.

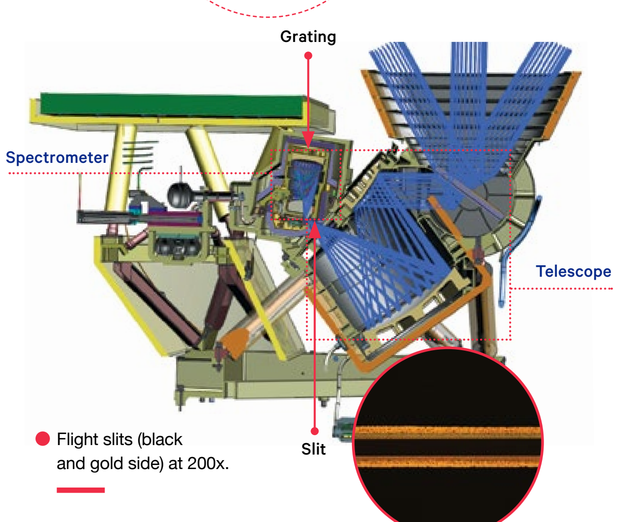
JPL's Diana Blaney is the Principal Investigator, and Karl Hibbitts, APL, is the Deputy Principal Investigator.

Telescope mirrors: TM1 polish complete, ready for coating.

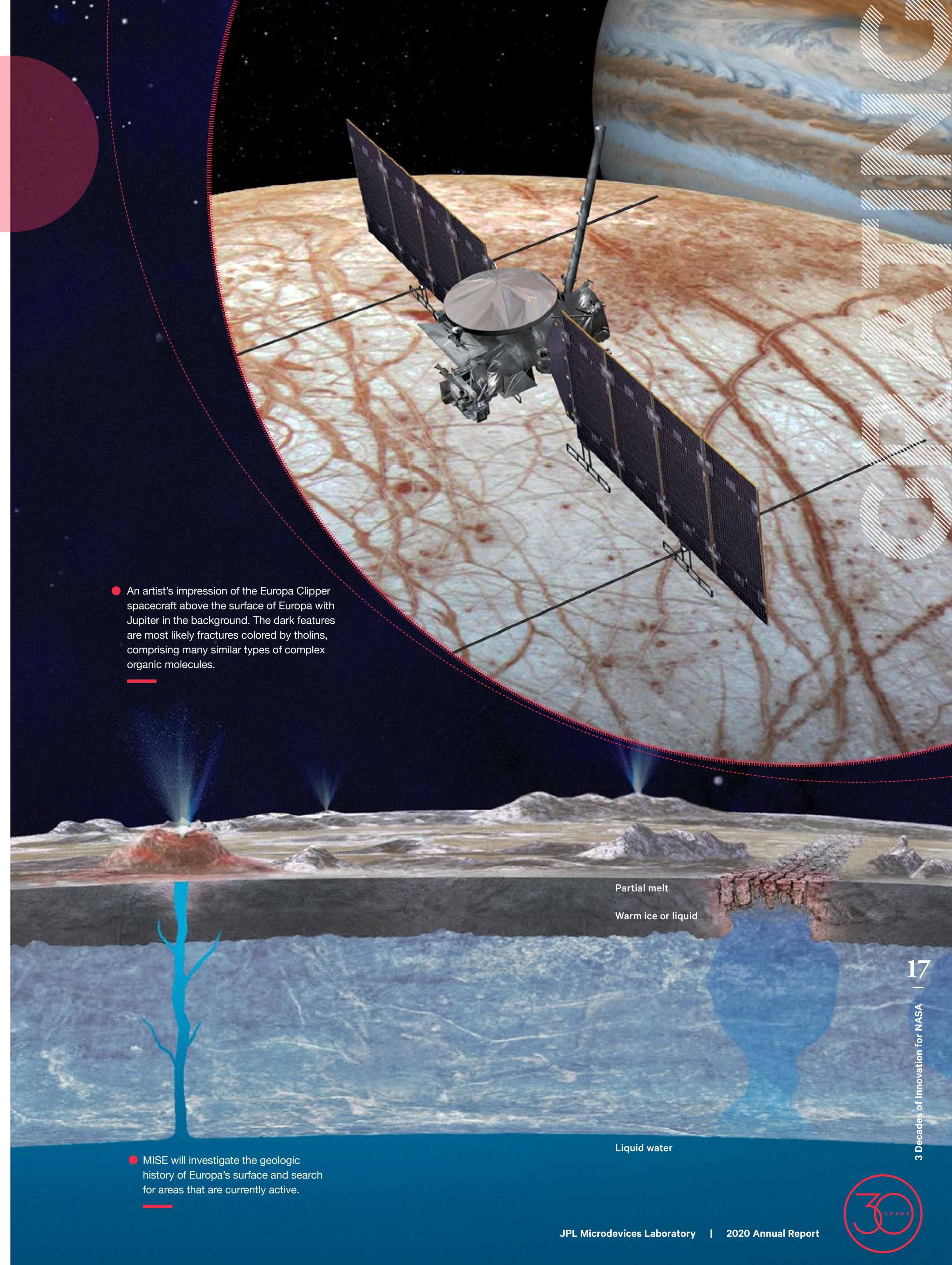
E-beam fabricated concave flight grating (JPL) with shaped efficiency to equalize signal over entire wavelength range.



MISE Dyson spectrometer optical design.

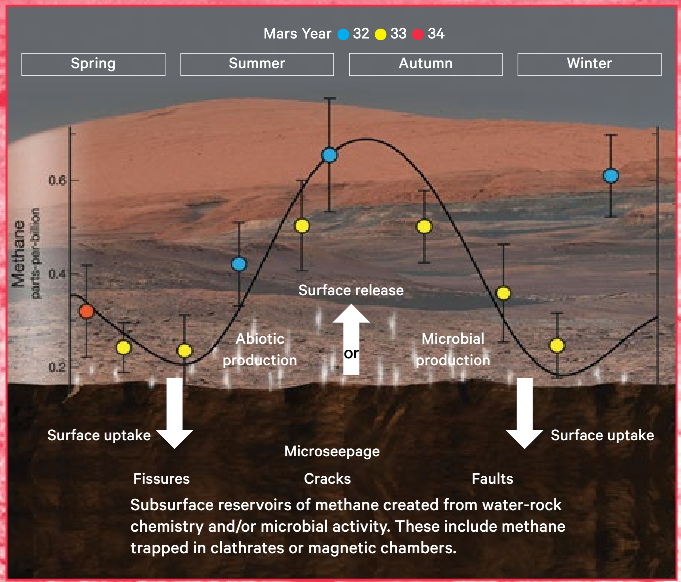


Flight slits (black and gold side) at 200x.

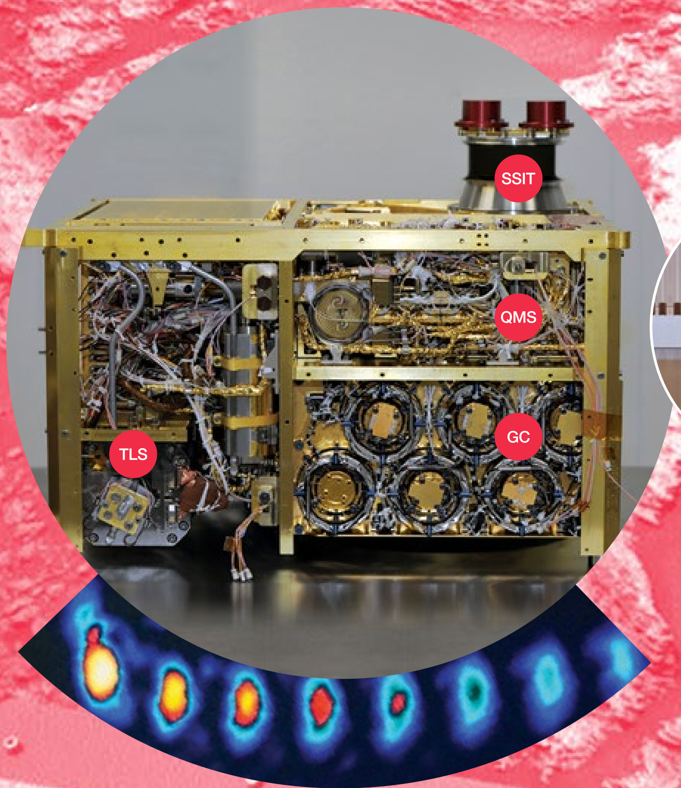


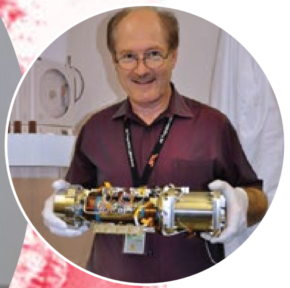
An artist's impression of the Europa Clipper spacecraft above the surface of Europa with Jupiter in the background. The dark features are most likely fractures colored by tholins, comprising many similar types of complex organic molecules.

MISE will investigate the geologic history of Europa's surface and search for areas that are currently active.



The Curiosity rover used SAM to detect seasonal changes in atmospheric methane in the Gale Crater. The methane signal has been observed for nearly three Martian years (nearly six Earth years), peaking each summer.





Dr. Webster holds a laboratory duplicate of the Mars TLS instrument to be used for testbed studies.

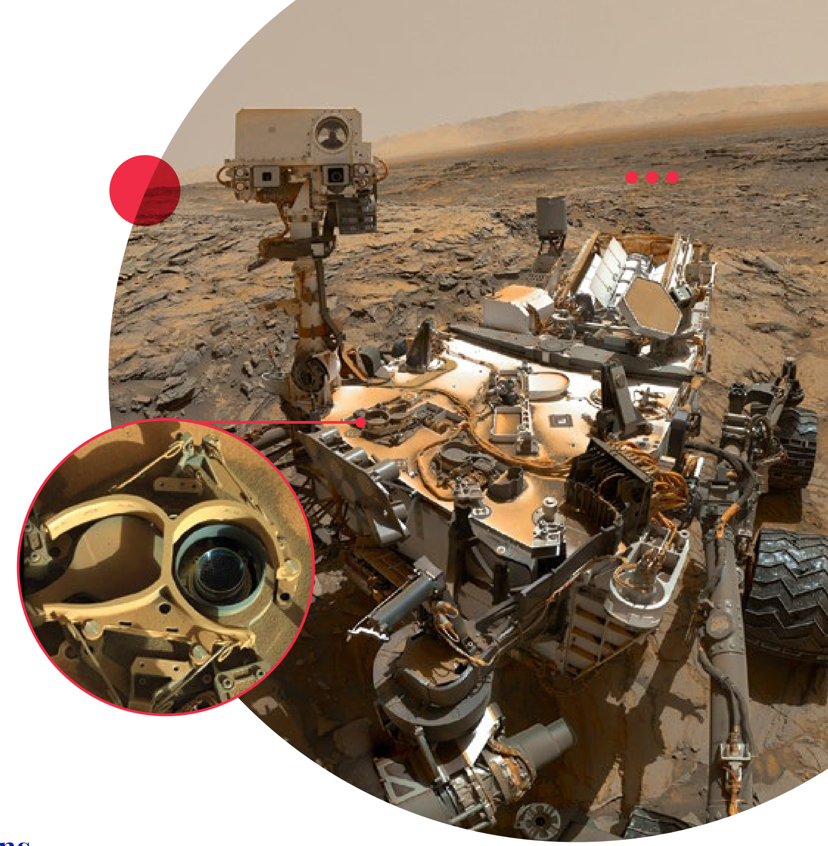
SAM instrument suite that will analyze the chemical ingredients in samples of Martian atmosphere, rocks and soil during the mission of NASA's Mars rover Curiosity.
TLS. Tunable laser spectrometer.
QMS. Quadrupole mass spectrometer.
GC. Gas chromatograph.
SSIT. Solid sample inlet tubes.

Infrared camera image shows the first 8 of the 40 bounces of the TLS lasers on the Herriott cell far mirror. Each spot is about 1 mm in diameter.

CURIOSITY

TLS returns high-impact science

TLS has paved the way for semi-conductor lasers to play an important role in future planetary science missions, with applications in spectroscopy, laser altimeters, and metrology.



This subframe image shows the covers in place over two sample inlet funnels of the rover's SAM instrument suite.

Curiosity took this image with its Mastcam on Feb. 10, 2019 (Sol 2316). The rover is currently exploring a region of Mount Sharp nicknamed "Glen Torridon" that has lots of clay minerals.

METHANE

As part of the Sample Analysis of Mars (SAM) suite, the JPL's Tunable Laser Spectrometer (TLS) uses infrared semiconductor lasers designed and fabricated at MDL specifically for sample analysis at 2.78 and 3.27 µm wavelengths. These lasers are used to make key measurements of Martian gas abundances and targeted isotope ratios, both in the atmosphere and as evolved from heating solid samples. In addition to high-sensitivity determination of atmospheric methane abundance, TLS is particularly suited to measuring very precise isotopic ratios in stable species, such as D/H and $^{18}O/^{16}O$ in water, $^{13}C/^{12}C$ and $^{18}O/^{17}O/^{16}O$ in carbon dioxide and $^{13}C/^{12}C$ in evolved methane. These measurements have informed us of atmospheric composition and loss, transport, seasonal cycles, geological processes and planetary evolution.

TLS has achieved noteworthy successes reported in several papers in Science magazine; these publications have received international attention in hundreds of news stories worldwide. Findings include detection of low background levels of methane on Mars at 0.4 parts per billion by volume (ppbv) that occasionally spike to higher levels, once as high as 20 ppbv. Monitoring the sub-ppbv background level over approximately six years has revealed a repeatable seasonal cycle in nighttime methane.

Moreover, recent daytime measurements show that the background seasonal cycle is a nighttime phenomenon, an observation supported by surface-atmosphere modeling studies. TLS measurements of D/H in water evolved 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 CO_2 isotope ratios on Mars at unprecedented accuracy of a few parts per thousand further show that the Martian atmosphere has changed little in 4 billion years. The carbon-13 and carbon-12 results form a balance between atmospheric loss and carbonate formation, a key result for models of planetary evolution.

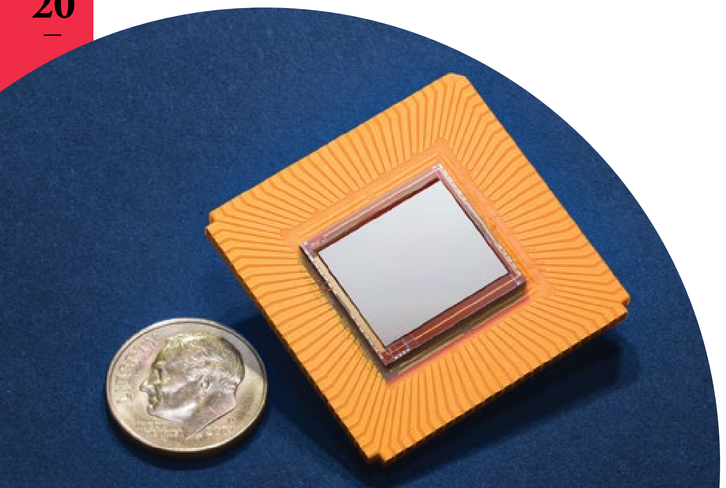
Now in its seventh year on Mars, the TLS instrument is performing exactly as it did on Earth when it was delivered for integration into the Curiosity rover; there has been no deterioration in performance or capability. As a result of its success, TLS instruments have been proposed for several New Frontiers and Discovery planetary missions, including as Venus and Saturn entry probes and as part of a Ceres lander for surface chemical analysis. Miniaturized versions of TLS instruments are going to the International Space Station (ISS), are part of the NASA astronaut space suit and Orion respiratory monitor, and have been deployed for several commercial applications, such as methane detection for the Pacific Gas and Electric Company (PG&E) and hydrogen sulfide detection in Chevron pipelines.

The laser technology integral to the performance of TLS was originally developed at MDL by team led by Drs. Rui Yang and Siamak Forouhar. Dr. Chris Webster is the Principal Investigator.

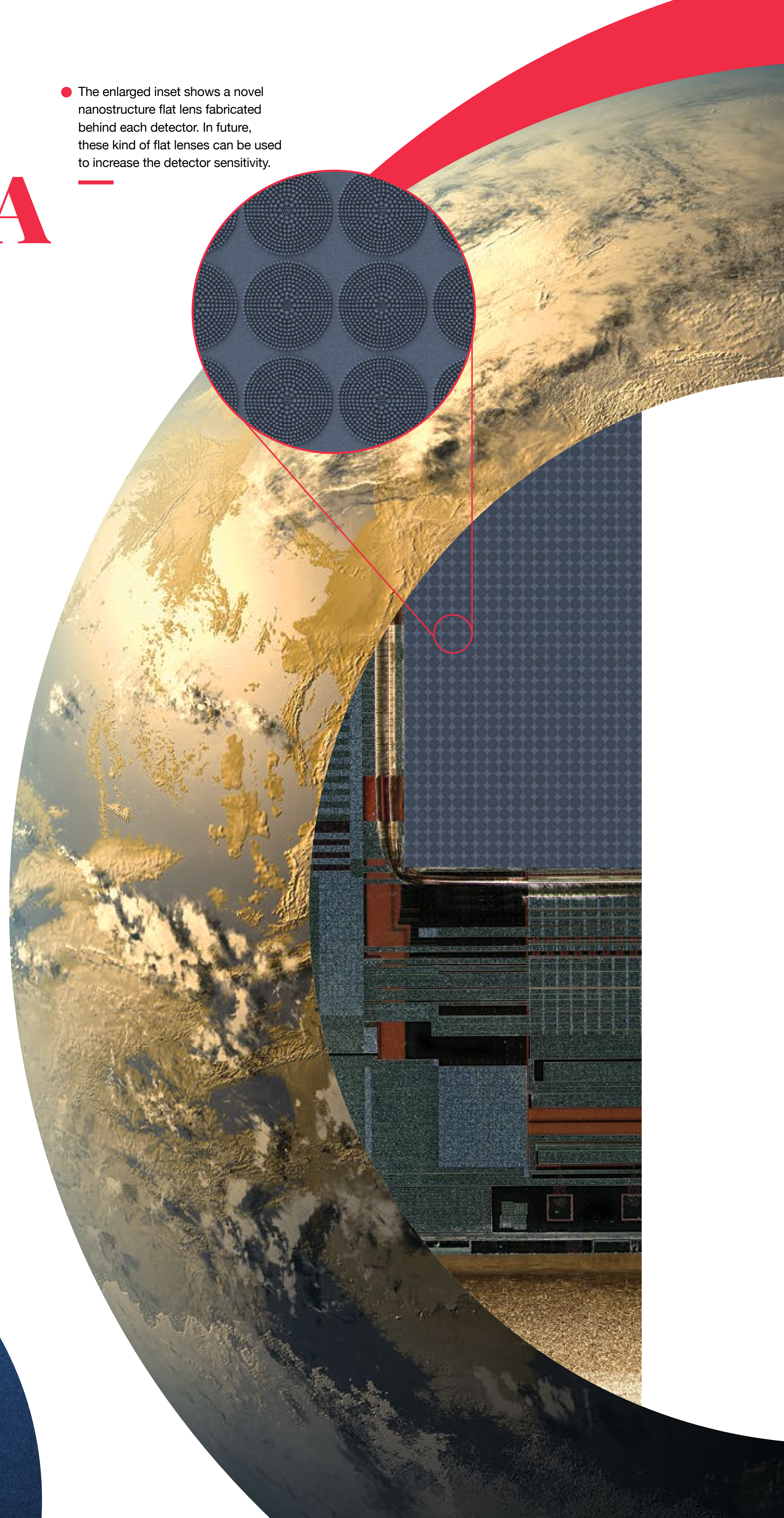
HyTI BIRD FPA

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

The Hyperspectral Thermal Imager (HyTI) is an instrument technology demonstration funded by NASA's Earth Science Technology Office under the In-Space Verification of Earth Science Technology program. The HyTI payload is designed to fit in a 6U CubeSat planned for low Earth orbit. A Long-Wavelength Infrared (LWIR) Barrier Infrared Detector (BIRD) will serve as the detector for HyTI's Focal Plane Array (FPA) and enable the HyTI mission. BIRD technology, which was developed and patented by JPL, is based on band-gap engineering of multilayer growth of III-V semiconductor compounds. The technology makes it straightforward and cost effective to design, grow and process the material and exploit the band-gap adjustability of high-performance detectors. BIRDs are grown on GaSb substrates at MDL using a molecular beam epitaxy machine. The resulting wafers, where the detectors are grown on the substrates, are screened, and better-performing wafers are manufactured into FPAs.



A HyTI focal plane array mounted onto a leadless chip carrier.



The enlarged inset shows a novel nanostructure flat lens fabricated behind each detector. In future, these kind of flat lenses can be used to increase the detector sensitivity.

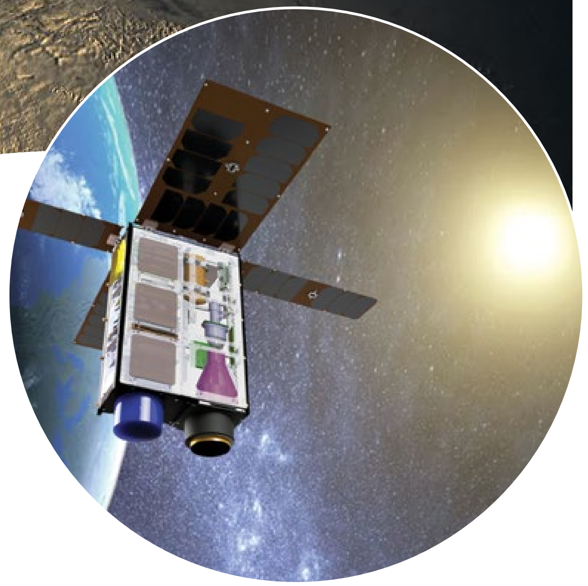
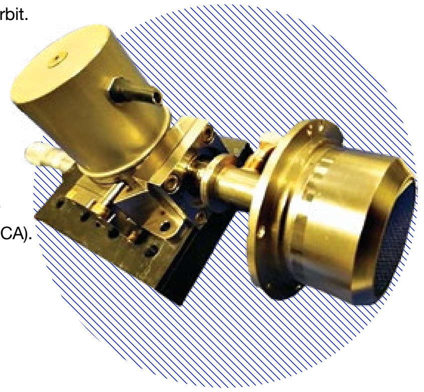
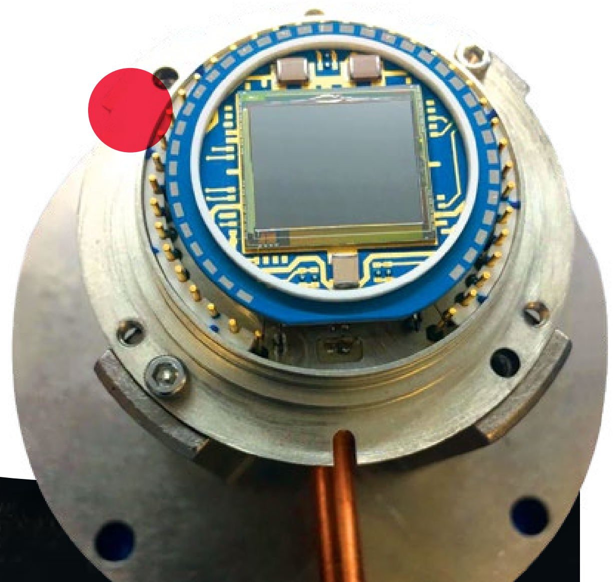


Illustration depicting the HyTI CubeSat in low Earth orbit.



An Integrated Dewar Cooler Assembly (IDCA).



FPA mounted on cold finger before IDCA integration process.

The manufacturing process involves detector array processing, read out integrated circuit hybridization and epoxy backfilling, substrate removal via diamond point turning, and low-temperature FPA characterization. High-operability, high-quantum-efficiency, high-uniformity, and high-yield long-wavelength infrared FPAs with elevated temperatures and low dark currents are selected for the anti-reflective coating process to reduce the reflection between the interface of the vacuum and FPA surface.

This process increases absorption of infrared light, as well as the signal-to-noise ratio, which allows operation with enhanced sensitivity. The packaging of the FPA into an integrated dewar cooler assembly requires precision and a specialized manufacturing process because a Fabry-Perot wedge filter is mounted just above the FPA surface. Alignment and mounting of FPA to ceramic carrier, cold shield to ceramic carrier, and ceramic carrier to cold finger are critical steps. Finally, referencing of the FPA optical center and orientation relative to an external structure eases the alignment of the FPA and telescope.

This no-moving-parts hyperspectral imaging technique is unique for its collection of the spectrum at each pixel, which corresponds to a target with a fixed area on Earth. The mission's objective is to analyze the collected data cube (spatial, spectral and temporal) to obtain important information on hydrological dynamics and land surface temperature. Importantly, this information can then be used for water resource management for agricultural applications. Because the CubeSat and Earth are in relative motion, the ground speed and frame rate will be synchronized so that the adjacent pixel along the direction of motion will image the same fixed-area target as the previous adjacent pixel. However, the Fabry-Perot wedge filter between the telescope and FPA introduces a varying optical path difference on the FPA along the direction of motion. From the collection of frames, an interferogram can be constructed for each target. A fast Fourier transform of the interferograms allows for the extraction of spectral radiance information and constructions of spectral images of the target.

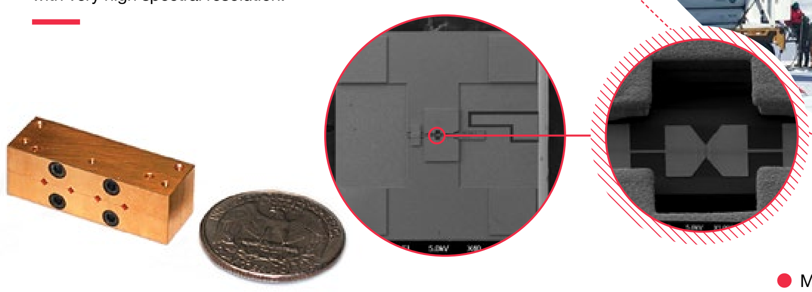
HyTI is a joint project in collaboration with Drs. Robert Wright, Paul Lucey, and Luke Flynn at the University of Hawaii; Dr. Miguel Nunes at the Hawaii Space Flight Laboratory; and Dr. Tom George at SaraniaSat, Inc. NASA awarded the HyTI proposal in 2018 and selected it in 2019 to fly in late 2021 or later as part of its CubeSat Launch Initiative.

HyTI FPAs are being developed by Drs. Sarath Gunapala, Sir (Don) Rafol, David Ting, Alexander Soibel, Brian Pepper, Sam Keo, Arezou Khoshakhlagh, and Cory Hill at JPL.

RECEIVER

This Hubble image shows the spiral galaxy Messier 83, also known as the Southern Pinwheel Galaxy. At 15 million light years from Earth, this galaxy has presented many supernova explosions and may have a double nucleus at its core.

Terahertz Schottky diode based sources and superconducting HEB mixers developed at MDL can be used to observe star-forming regions with very high spectral resolution.



MDL designed and fabricated instrumentation is scheduled to fly via a high-altitude stratospheric balloon for three weeks in the skies above Antarctica in December 2023, offering new astronomical observational opportunities in the far-infrared via supercooled superconducting high-spectral-resolution detectors.

ASTHROS balloon mission

For millennia, humans observed the heavens with the naked eye. Although Galileo did not invent the telescope, in the early 1600s, he became the first to systematically use one for astronomy. Astronomical and astrophysical observations have since benefited from other similarly transformational improvements in technology. For example, satellite-borne telescopes can be used to avoid the problems inherent to viewing through Earth's atmosphere and to observe various parts of the electromagnetic spectrum. However, such missions come with very high costs and long lead times. Balloon-borne telescopes operating in the stratosphere offer substantial returns with substantially lower costs and lead times, and they can improve our understanding of how stars form within and outside the galaxy by greatly expanding the pool of available data.

The Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths (ASTHROS) builds on years of development of THz high-power sources and heterodyne array receivers at MDL. It is a 2.5-m (SOFIA-like size) balloon-borne observatory that will make the first detailed spectrally resolved high-spatial-resolution 3D map of ionized gas in galactic and extra-galactic star-forming regions via simultaneous observations of the 122 mm (2.459 THz) and 205 mm (1.461 THz) fine structure lines of ionized nitrogen. It provides a low-risk, low-cost stepping stone for future heterodyne missions.

A 21-day Antarctic flight in 2023 will focus on high-angular-resolution mapping of two template galactic star-forming regions and the entire disk of the M83 barred spiral galaxy. The resulting data will complement existing datasets from SOFIA, WISE, Herschel, Spitzer and HST. ASTHROS will be capable of tuning to nearby spectral lines (OH, HDO, HF, HD, CO) for target-of-opportunity observations. One compelling target is the HD 112 mm (2.674 THz) line that traces the gas mass distribution in protoplanetary disks. ASTHROS' resolution corresponds to 0.2 pc and 0.35 pc at 122 mm and 205 mm, respectively, for a source 4 kpc from the sun. This high angular resolution will enable the resolution of structures ~750 times smaller than the typical size of star-forming regions (~150 pc).

ASTHROS has been selected by NASA to fly from Antarctica in 2023 and will be the first long-duration balloon mission led and managed by JPL. At its heart is a camera with MDL-produced terahertz heterodyne technology.

By combining high-resolution mapping with large-scale mapping, we will begin to understand how different stellar feedback mechanisms affect ionized gas over a wide range of spatial scales in the Milky Way and the M83 galaxy.

The ASTHROS payload will consist of a 4-pixel, dual-polarization, dual-band cryogenic superconducting heterodyne array camera for high-spectral-resolution imaging at 1.4-1.5 THz and 2.4-2.7 THz. The instrument design features a straightforward receiver architecture based on MDL-produced state-of-the-art ultra-broadband GaAs Schottky diode-based frequency-multiplied local oscillator sources and NbN hot electron bolometer (HEB) mixers. Using a patented device topology, the ASTHROS receivers will be able to cover many key spectral lines with a single receiver, enormously increasing the scientific return. ASTHROS will fly a 4-K-class low-power cryocooler for the first time and thus will not require liquid helium, enabling extended-lifetime missions.

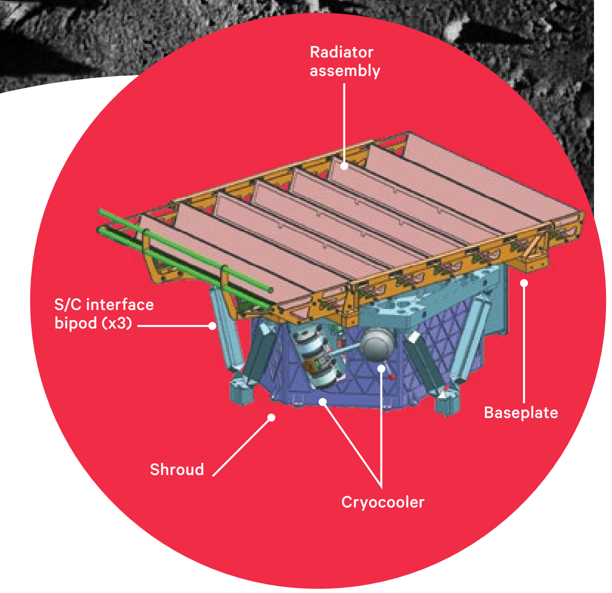
By flying the latest MDL-produced THz heterodyne technology, ASTHROS will serve as a pathfinder for the Origins Space Telescope (OST), future NASA probe-class missions, or small satellite missions.

ASTHROS is the first long-duration balloon mission led and managed by JPL. JPL will also build the payload. Jorge Pineda, Jose V. Siles and Jonathan Kawamura of JPL are the Principal Investigator, Project Manager and Systems Engineer, respectively. MDL engineers Choonsup Lee and Bruce Bumble will be fabricating components essential to the submillimeter camera.

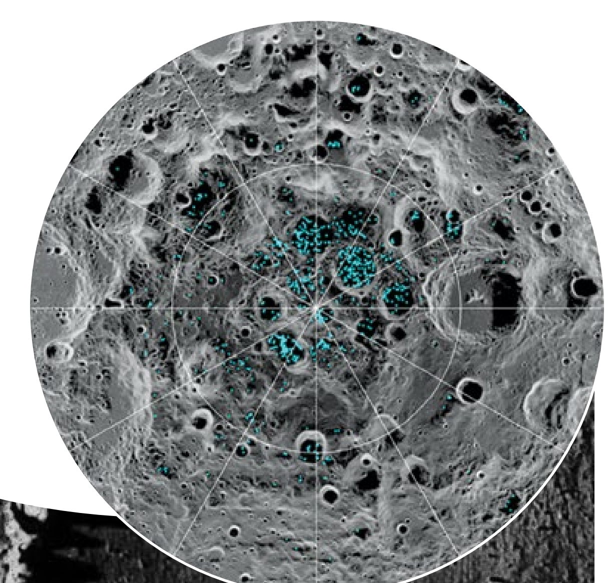
ASTHROS partners include the John Hopkins University's Applied Physics Laboratory, Arizona State University and the University of Miami.

Lunar trailblazer mission

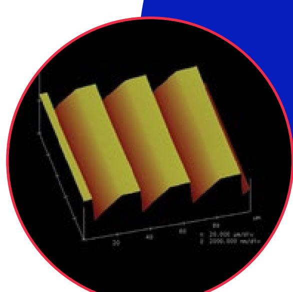
HVM^3 will help to understand the distribution of and change in volatile abundance over time on the lunar surface.

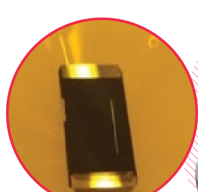


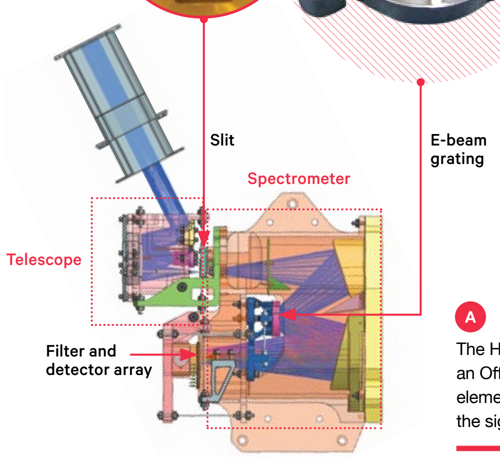
The High-resolution Volatiles and Minerals Moon Mapper instrument is a pushbroom shortwave infrared (SWIR) imaging spectrometer. With a spatial resolution of 70 m/pixel over a 20 km swath width and a spectral resolution of 10 nm over a spectral range of 0.6 to 3.6 µm, HVM^3 is optimized for the detection of volatiles to map OH, bound H_2O, and water ice.



The image shows the distribution of surface ice at the Moon's south pole—blue represents the ice locations. The ice is concentrated at the darkest and coldest locations, in the shadows of craters. M3, aboard the Chandrayaan-1 spacecraft, launched in 2008, was uniquely equipped to confirm the presence of solid ice on the Moon.







A

The HVM^3 spectrometer and telescope, an Offner design with reflective optical elements and a grating tuned to improve the signal in long wavelengths.

The goal of the Lunar Trailblazer mission is to understand the form, abundance and distribution of water on the Moon and the lunar water cycle. It is a SmallSat mission that will use the High-resolution Volatiles and Minerals Moon Mapper (HVM^3) instrument, which is an evolution of the Moon Mineralogy Mapper (M3). M3 was one of two instruments that NASA contributed to India's first mission to the Moon, Chandrayaan-1, which launched on October 22, 2008. Like M3, an imaging spectrometer that discovered and mapped pervasive water/hydroxyl (OH) signatures on the Moon, HVM^3 builds on grating technology designed, developed and fabricated at MDL.

M3 paved the way for confirmatory observations and re-analyses by other instruments. However, its limited spectral range, instrument sensitivity, and spatial coverage left several key questions unanswered. The new HVM^3 instrument is an Offner imaging spectrometer based on a JPL developed Ultra Compact Imaging Spectrometer (UCIS) design and will resolve many of these issues. First, it will determine whether observed signatures are due to adsorbed molecular H_2O, H_2O in ice form, or OH. HVM^3's spectral range extends to 3600 nm, which captures the extended absorption shapes of OH, water ice, and molecular H_2O and will allow for their direct detection and mapping.

Second, it will determine if and where permanently shadowed regions (PSRs) harbor water ice. Recent M3 data suggest that PSRs contain water ice. If true, this finding could guide future scientific sampling or resource extraction efforts on the lunar surface. HVM^3 aims to answer this question with unprecedented sensitivity. It will enable direct observations within PSRs using terrain-scattered solar illumination, for which it will provide SNR ≥ 50 in discriminative spectral intervals.

Third, HVM^3 will help to understand the contribution of thermal emission effects to estimates of water abundance. HVM^3's extended spectral range will capture the entire absorption feature with both ends of the continuum, providing unprecedented power to fit reliable and accurate thermal emissivity curves to allow unbiased estimations of lunar water deposits. Trailblazer's Lunar Thermal Mapper instrument provides simultaneous direct temperature measurements at longer wavelengths.

Finally, HVM^3 will help to understand the distribution of and change in volatile abundance over time across the lunar surface. The observation plan includes repeat revisits to selected polar and midlatitude locations at many phase angles. Measuring the lunar surface's volatile deposits at multiple times of the solar day will reveal any diurnal variability in water availability. Figure A shows the optical layout: it is made entirely of reflective surfaces and uses a dispersive grating with efficiency tuned to improve signal in the low-illumination, longer-wavelength regions of the spectrum.

Bethany Ehlmann of JPL and Caltech is the Principal Investigator, and MDL's Director Robert Green is one of the Co-Investigators. Other JPL scientists involved include David Thompson, another Co-Investigator and the HVM3 Instrument Scientist, and Diana Blaney, a collaborator.

LCMS lunar instru-ment

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

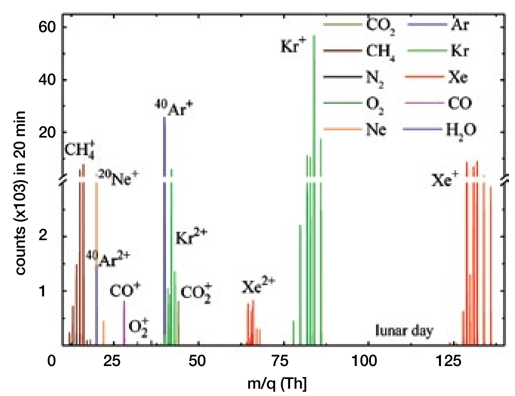
Although we now know that the Moon has an extremely thin atmosphere, it was not known in 1972 when Harrison "Jack" Schmitt walked on its surface.

ATMOSPHERE

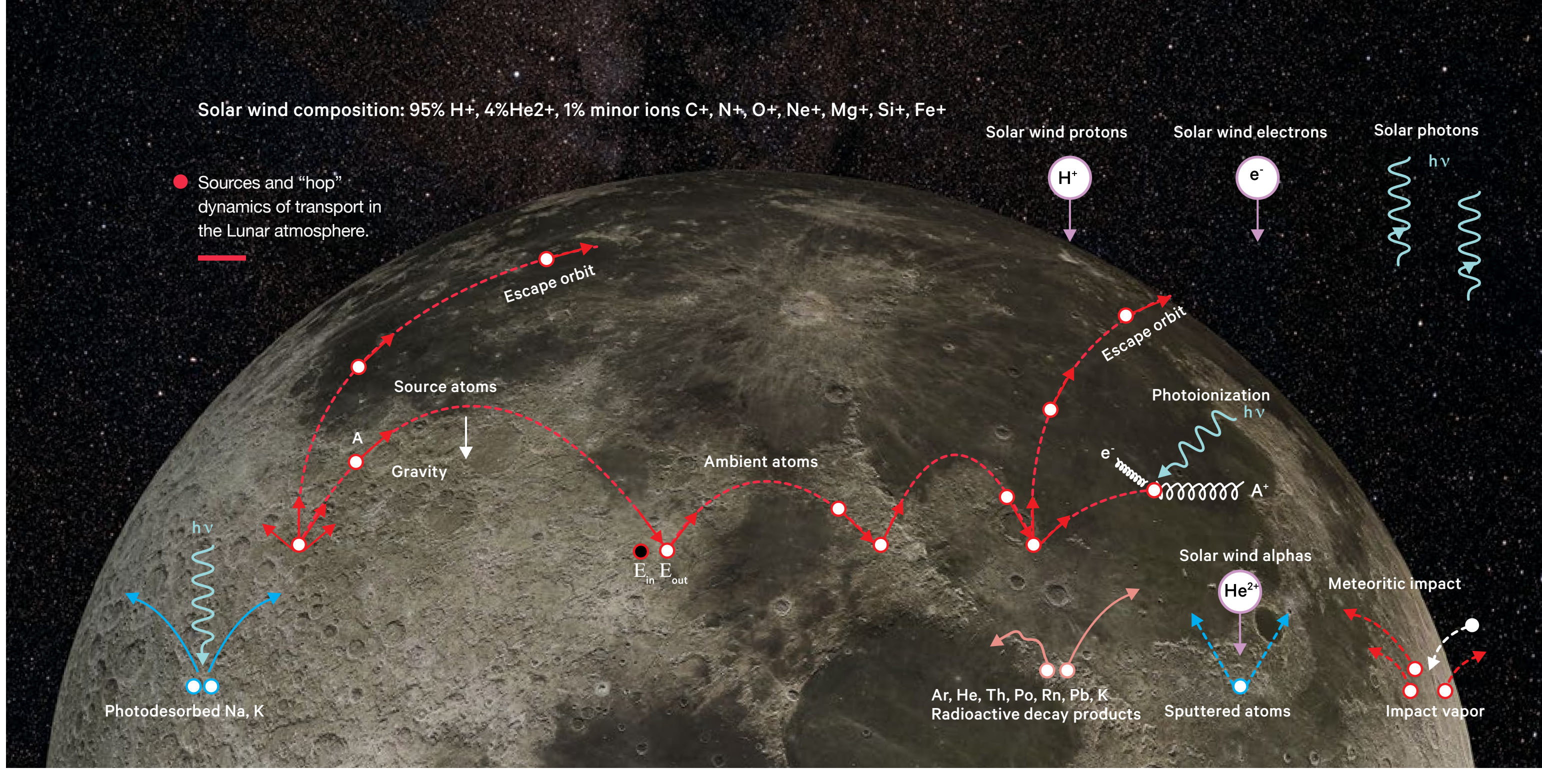
The Moon is not dead; it even has a water cycle. The JPL mass spectrometer has been improved upon for more than 25 years. The latest development, the Lunar CubeSat Mass Spectrometer (LCMS) funded under the NASA Development and Advancement of Lunar Instrumentation (DALI) program, is being developed at MDL to investigate the Moon's vanishingly thin atmosphere.

The Moon was long thought to have no atmosphere. However, many processes are now known to contribute to the lunar atmosphere, which contains water vapor and changes in a diurnal cycle. The lunar atmosphere's composition and density result from a balance between production and loss; the balance varies over time. The lunar atmosphere is primarily created via solar wind sputtering, thermal desorption, photo-desorption, radioactive decay, and meteoric bombardment. It is lost via kinetic gravity escape, freezing out, photoionization capture by the solar wind or Earth's magnetosphere, and bonding to chemically active surface atoms. The key questions are: how does each of these processes vary with time, and how might they relate to the characteristics of the solar wind? These questions became even more significant after surface water was discovered on the Moon, and especially given the possibility of ice in permanently shadowed regions (PSRs) and at the poles.

The instrument will measure the concentrations of volatiles at different times of the lunar day to test, calibrate, and refine models for the mobility of water and other volatiles on the lunar surface. These models will provide constraints on understanding polar ice sources. The instrument will also help understand how landed spacecraft perturb the fragile lunar atmosphere. The analytical core of the instrument is a quadrupole ion trap mass spectrometer (QITMS) that has been under development at JPL since 1994. It operated successfully on the International Space Station (ISS) from March 2009 to November 2011 as the main component of the Vehicle Cabin Atmospheric Monitor (VCAM) instrument.



Modeled LCMS measurements of the lunar daytime surface exosphere show that it can make the first Kr and Xe abundance measurements to 4% accuracy on ^{78}Kr and 0.5% on ^{84}Kr within 20 minutes on the lunar surface.



Sources and "hop" dynamics of transport in the Lunar atmosphere.

The same technology is currently in the descendent of VCAM, the Spacecraft Atmosphere Monitor (SAM), which was developed by and is being operated from within MDL and has been on the ISS since 2019.

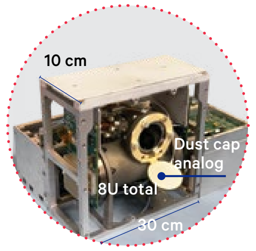
LCMS will be the first lunar instrument that can identify and quantify species in the lunar atmosphere with sufficient sensitivity and precision to answer key scientific questions about the lunar atmosphere. It can measure 10 molecules per cc. For context, 1 cc of air on Earth contains 2.9 x 10^{19} molecules. LCMS uses a QITMS with an unsurpassed combination of low mass (7 kg), low power (max 30 W with heater bulb on), high sensitivity (0.003 counts/cm^3/sec), and ultra-high precision (0.5% for noble gas isotope ratios over 24 hours) that is tenfold better than the demonstrated performance of any previous ITMS.

Since 2003, JPL's Mass Spectrometer group has been developing a three-dimensional QITMS (also known as a "Paul trap" MS) for space applications. QITMS is the preferred MS type: its fundamental design and operating parameters make LCMS the most sensitive QITMS-based mass spectrometer type in existence. The ionizing electron beam creates ions at the center of the 3D trap, where trapping efficiency is maximal and higher-order electrical fields that could distort the mass resolution are minimal. The QITMS is a "parallel" MS, meaning all ions created are also measured.

In contrast, linear quadrupole MS instruments detect only those charge-to-mass ratios they are programmed to visit in "mass-hopping" mode. All other created ions are lost. LCMS has two major assemblies: The Sensor Head Assembly, built by JPL, and the Main Electronics Assembly, built by the University of Michigan's Space Physics Research Laboratory (SPRL). The QIT Sensor is housed in a vacuum assembly constructed entirely of titanium and alumina together with small quantities of non-magnetic stainless steel fasteners. A "wireless" design holds it together in compression mode, ruggedizing it against launch, entry and landing environments. All the electronics boards (Sensor Head and Main Electronics Assembly) are built with flight-like parts and designed to operate in a vacuum over a broad temperature range up to 80°C.

Dr. Stojan Madzunkov of JPL is the Principal Investigator of the project and is collaborating with Dr. Dan Fry of the Johnson Space Center, a Co-Investigator and PI of LETS. Co-Investigators at SPRL are building the MS' Main Electronics Assembly. Jurij Simcic, Dragan Nikolic and Murray Darrach are the MDL Co-Investigators.

For this DALI project, the MS is being teamed with the Linear Energy Transfer Spectrometer (LETS), which will monitor the radiation environment of the surface.



Lunar CubeSat MS; bottom cover off.

The unique "wireless" QITMS.

The SAM instrument.

The VCAM system.

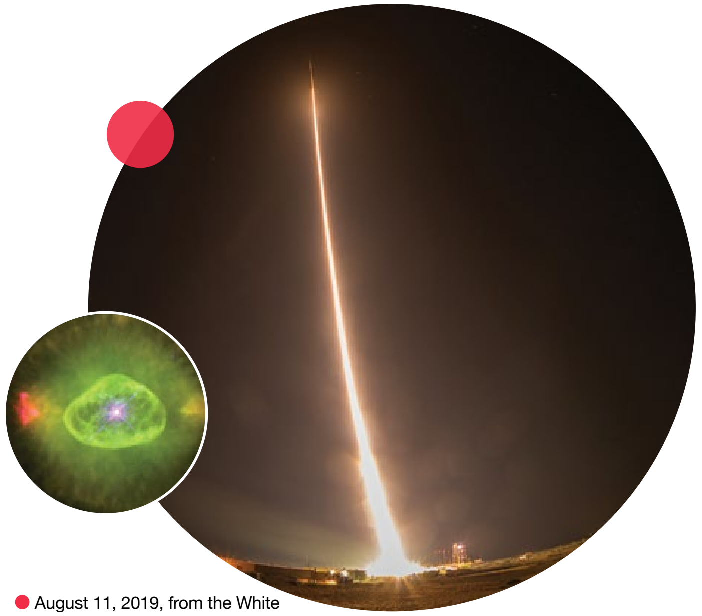
SISTINE suborbital observatory

The Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet host stars (SISTINE) was successfully launched for its first flight on August 11, 2019, carrying an enabling MDL technology.

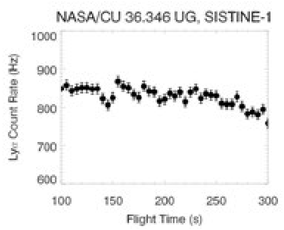
When searching for life on exoplanets, it is essential to avoid false positive results. For example, oxygen in Earth's atmosphere is produced by plants and is a sign of life. However, on a different planet, ultraviolet (UV) radiation from that planet's star could break down carbon dioxide in the atmosphere to release oxygen. Therefore, to unambiguously interpret observations of exoplanets, it is equally critical to examine their stars. The SISTINE sounding rocket studies stars to find which gases are valid signs of life. Observing in the far UV is not easy, but it has taken a major step forward due to MDL technology. SISTINE's 100 mm convex secondary mirror was overcoated at MDL using MDL's capabilities in atomic layer deposition of AlF_3. This coating resulted in high reflectivity in the far UV, including the challenging Lyman UV range, which is below the short wavelength cutoff of the Hubble Space Telescope. The MDL-produced coating gave SISTINE a spectroscopic capability 100 times that of Hubble.

SISTINE was successfully launched for its first flight, a calibration test. The small count rate decrease (see the figure above) was as the payload re-entered the atmosphere on the downward leg of the flight). The experiment, on a Black Brant 9 rocket, flew to 161 miles of altitude, observed Lyman-alpha (Lyα) signals with a good count rate, and descended by parachute allowing instrument recovery. With this successful initial test, a follow-on science flight is planned for the summer of 2020. The goal of this flight is to measure the UV radiation environment in the habitable zones around nearby stars. More than one UV wavelength must be examined to make scientific deductions.

Kevin France of the University of Colorado is the Principal Investigator of the project. In MDL, Shouleh Nikzad and April Jewell developed the approach, while John Hennessy is responsible for the technology delivery.



August 11, 2019, from the White Sands Missile Range (NM). Shown below is NASA/CU 36.346 UG, Aug 11 2019, WSMR.



SISTINE aims to study how the outer envelope of stars is dispersed back into the interstellar medium by observing the science target NGC 6828, a planetary nebula (Inset).

No previous or current observatory offers simultaneous spectral coverage of these important UV wavelengths. Owing to the frequent yet aperiodic and abrupt time variability of these sources, simultaneous observation of spectral tracers probing a range of stellar atmospheric layers is essential.

Flares can alter UV luminosity by factors of 10 on timescales of seconds, and even non-flaring states show stochastic fluctuations of ~30% per minute timescales. Furthermore, Hubble Space Telescope observations typically require two instrument configurations to simultaneously acquire both Lyα and C IV observations.

SISTINE was designed specifically to address these technical hurdles and to provide the most robust stellar irradiances for state-of the–art terrestrial atmosphere models. SISTINE provides a broad bandpass (100–160 nm) to simultaneously cover O VI through C IV, employs advanced optical coatings providing sufficient sensitivity to measure a suite of lines in a single observation, and utilizes a new imaging spectrograph design providing the spatial resolution needed to robustly subtract geocoronal Lyα and to resolve nearby binary exoplanet host star systems.

Successful use of a high-reflectivity UV mirror and UV detector for SISTINE will help test this technology on a relatively modest mission for use in future orbiting observatories. These missions will complement the observations to be made by the James Webb Space Telescope (JWST) scheduled to launch in 2021. SISTINE's UV contribution will be invaluable in interpreting the JWST's visible to mid-infrared observations. SISTINE's technology is a pathfinder for future UV instrumentation baselined by the flagship Large UV/Optical/IR Surveyor astrophysics mission concept.

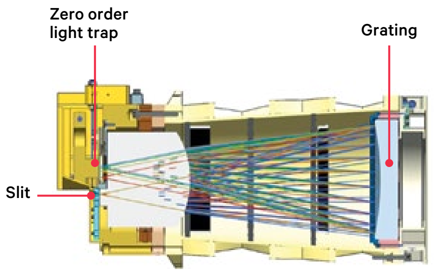
EMIT on ISS

EMIT will use an imaging spectrometer mounted to the exterior of the ISS to determine the mineral composition of natural sources of dust aerosols worldwide.

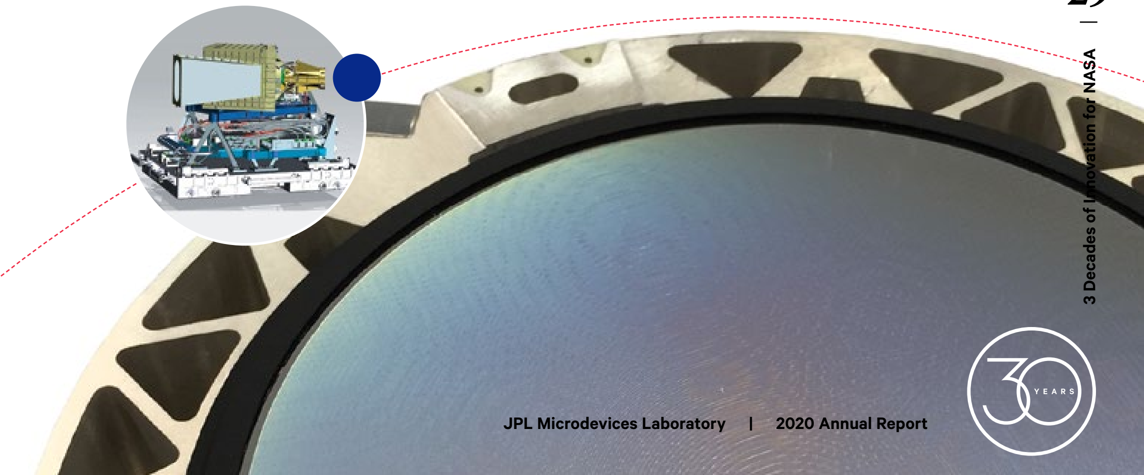
In the arid land regions of planet Earth, fine-grained mineral dust is routinely blown into the atmosphere, where it reacts with many elements of the Earth system. Depending on the mineral dust's composition, it can absorb light and heat the atmosphere or reflect light back to space and cool the atmosphere. Today, the effect of mineral dust on cooling or heating is uncertain on both the local and global scales. Modern Earth system computer models are ready to address this question but lack accurate information on surface mineral composition.

The science objectives of the Earth Surface Mineral Dust Source Investigation (EMIT) are focused on understanding and reducing uncertainty about the role of mineral dust aerosols in heating or cooling the Earth at the regional and global scales.

NASA has selected EMIT to close this knowledge gap. On the International Space Station (ISS), EMIT will use state-of-the-art imaging spectroscopy enabled by MDL components to measure the spectral signatures of the minerals in arid land regions.



High-throughput imaging spectrometer design enabled by MDL components.



EMIT instrument design for the International Space Station.

MDL-e-beam-fabricated structured blaze concave grating technology for the EMIT prototype imaging spectrometer.

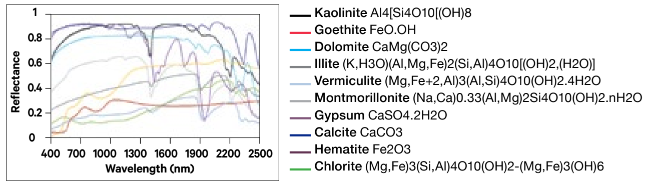
Arid land regions of the Earth that will be measured by EMIT.

Snaptshot of mineral dust of differing composition being emitted into the Earth's atmosphere.

The EMIT instrument is a high-optical-throughput Dyson imaging spectrometer that measures from the visible to the short wavelength infrared portions of the electromagnetic spectrum with fine spectral sampling. The key minerals (hematite, goethite, illite, vermiculite, calcite, dolomite, montmorillonite, kaolinite, chlorite, and gypsum) needed for the EMIT science objectives have unique spectral signatures in this range. The EMIT imaging spectrometer requires a specialized concave reflection grating, optical slit, and zero-order light trap that are fabricated using MDL's unique combination of equipment and processes.

EMIT is currently under development at JPL and is planned to launch to the ISS in 2022, where it will begin making measurements and achieve NASA's science objectives. All EMIT spectroscopic measurements will be calibrated and made available to the wider science community to support a broad range of additional Earth science studies.

Robert Green is the Principal Investigator, and JPL Co-Investigators are Olga Kalashnikova and Vincent Realmuto in the JPL Science Division.



Spectral signatures of minerals that are the focus of the EMIT investigation.

CLIMATE

Roman telescope

This NASA observatory will unravel the secrets of dark energy and dark matter, search for and image exoplanets, and explore many topics in infrared astrophysics.

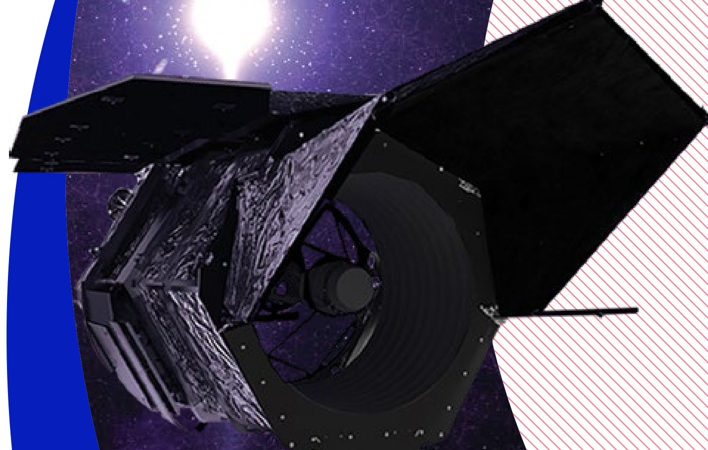
The WFIRST mission was renamed to honor a NASA pioneer and is now the Nancy Grace Roman Space Telescope. It is commonly known as the Roman Telescope.

JPL's Coronagraph Instrument (CGI) will be a crucial part of the Roman Space Telescope mission, which is slated to launch in the mid-2020s. CGI is a technology demonstration designed to suppress host starlight to 10^{-8} - 10^{-9} to contrast over a chosen region of the image plane and spectral band to observe and spectrally characterize extremely faint exoplanets in the visible to near-IR spectral range. MDL is fabricating occulting masks and aperture stops for the two CGI operating modes, a Hybrid-Lyot Coronagraph (HLC) and a Shaped Pupil Coronagraph (SPC).

The HLC occulting mask is positioned at the focal plane of CGI and will both reflect and diffract the light of the star, which will be blocked by the downstream Lyot stop. Fabricated on an antireflection-coated glass substrate, the HLC mask is a metal spot with a precisely aligned grayscale electron-beam-profiled dielectric pattern on top. The complex dielectric pattern was carefully optimized by the CGI mask design team to fulfill two functions. First, it will modify the phase of the partially transmitted light, creating an extremely dark region around the star to allow exoplanet imaging. Second, it will modify the phase of the reflected light to allow low-order wavefront sensing (LOWFS) and control of the CGI optics. The dielectric pattern can be non-circularly symmetric.

Bowtie masks with LOWFS phase dimple on an AR-coated glass substrate.

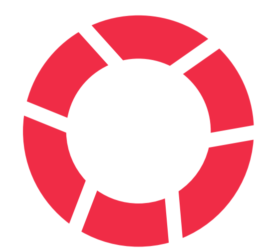
Dr. Nancy Grace Roman is shown with a model of the Orbiting Solar Observatory (OSO) in 1962.



The Roman Space Telescope's 300-megapixel Wide Field Instrument will measure a sky area 100 times larger than Hubble can measure. This means a single Roman Space Telescope image will hold the equivalent detail of 100 pictures from Hubble.

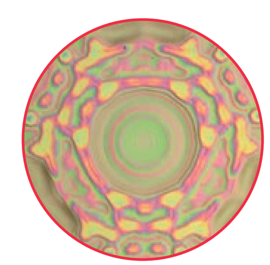
Shaped pupil spectroscopy mode mask.

Shaped pupil wide-field imaging mask.

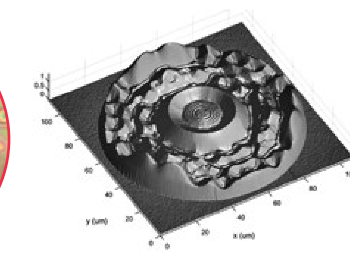


Silicon aperture of hybrid-Lyot stop.

Wide-field Lyot mask for SPC.



Microscope photo of fabricated HLC occulting mask.



Atomic force microscope measurement of the surface profile of a prototype HLC occulting mask.

MASKS

The CGI SPC utilizes masks that are designed to be mounted in a pupil plane of the instrument and operate in reflective mode to avoid chromatic transmission effects. They serve to shape/apodize the pupil amplitude for high-contrast spectroscopic and wide-field imaging modes. They consist of binary patterns of highly reflective ~20-μm pixels surrounded by extremely black regions forming a roughly 20-mm-diameter aperture. These precisely designed diffractive patterns are fabricated at MDL on silicon substrates; the reflective pixels are aluminum coated, and the black regions are cryogenically etched into needle-like structures to produce <10^{-7}-level reflectivity. The CGI-SPC also requires a focal plane mask for LOWFS and control, and it takes the form of a metal bowtie-shaped aperture on antireflection-coated glass. The metal pattern has a central elliptical dimple with precisely controlled depth to provide the proper reflection and phase for LOWFS. Several of these MDL-fabricated masks have been successfully tested in JPL's High Contrast Imaging Testbed (HCIT), demonstrating the performance required to meet NASA milestones.

Both CGI-HLC and CGI-SPC require different Lyot stops to achieve the required high-contrast performance at the 10^{-9} level in the final image. These stops are fabricated at MDL using deep reactive ion etching through silicon wafers and are coated with metal for opacity.

CGI contains two deformable mirrors (DMs) manufactured by Northrop Grumman's AOA Xinetics (AOX), each allowing exquisite control of the optical wavefront, achieving better than a 20-pm incremental step size on each of 2304 independent actuators within an area of approximately 3.5 square inches (a pm, or picometer, is one billionth of a millimeter). In that same electrical interconnect real estate, there are 96 actuators linked together to form grounding reference bars, for a total of 2,400 pins with nearly no margin for shorts or opens. The extreme density of interconnecting wires and pins within such a small area creates a number of fabrication challenges. The first is how to ensure that electrical isolation and positional registration can be maintained for the interface between the capacitor electrodes of the DM and the gold pads that will be used to ensure electrical contact to the connectors and cables that provide power to the mirror. MDL performs photo-lithography to precisely deposit these gold pads on the back side of the AOX DM — a very important step in the DM fabrication process. MDL has developed a unique fabrication process using photoresist spray coating, unique fixturing for contact lithography, and liftoff metallization patterning to ensure the tight precision and accuracy needed for the interconnect, which is required for the DM's function.

The contributors at MDL for the CGI work are primarily Dan Wilson, Victor White, Karl Yee, Frank Greer, Ilya Poberezhskiy, Rich Muller, Pierre Echternach and Bala K. Balasubramanian. The designs come from A.J. Eldorado Riggs and the CGI mask design team.

Left their mark

From its inception, MDL has been fortunate to benefit from the contributions of extremely talented and skilled individuals. They made their mark here and then went on to conquer new challenges elsewhere.

PAUL MAKER | RETIRED 1987

Dr. Maker joined JPL in 1987 after a successful career in non-linear optics at Ford Research Laboratories. His role was to lead MDL's effort in Electron Beam Lithography, and until he retired in 2002, he utilized the e-beam's unmatched precision to develop novel fabrication processes that are still in use today. He invented direct-write e-beam techniques for creating grayscale surface-relief patterns, enabling the fabrication of high-efficiency diffractive optics including blazed gratings, lenses, and computer-generated holograms. More importantly, he invented e-beam methods for fabricating such grayscale diffractive optics on convex and concave substrates, even though the e-beam tool was designed to write on flat wafers. The ability of MDL to make convex and concave gratings has enabled JPL to develop and fly multiple airborne and spaceborne imaging spectrometers for NASA missions. Paul Maker was awarded the NASA Exceptional Achievement Medal in 2002.

FRANK J. GRUNTHANER | RETIRED 1973

Dr. Grunthaner came to JPL from Caltech in 1973 after his PhD. Awarded the NASA Exceptional Scientific Achievement Medal, he and Dr. Paula Grunthaner invented the delta-doped CCD approach that gave orders of magnitude improvement in device imager performance. He developed the science and technology for the Mars Oxidation Instrument (MOx) for Mars 96 (a failed Mars mission launched in 1996). This was the first microchemical laboratory for spaceflight with key components from MDL. He developed the Urey Instrument Concept in collaborations with UC San Diego, UC Berkeley and NASA Ames, resulting in its initial inclusion in the ExoMars Pasteur Instrument Package. Dr. Grunthaner retired from JPL in 2012.

PAULA GRUNTHANER | RETIRED 1974

Dr. Grunthaner came to JPL in 1974 while still an undergraduate (Caltech BS, 1975; PhD, 1980) and stayed until retiring in 2012. Her experience included hands-on research and supervision of R&D efforts that included UV/vis, IR, sub-mm, nanotechnology, and lab-on-a-chip sensors and instrumentation. In 1995, she received a NASA Engineering Award for development of UV-sensitive delta-doped CCDs. After taking other roles in JPL, she returned to MDL as the manager of the In Situ Instrument Systems section with the responsibility to oversee MDL activities and initiate a cultural transition to 'success is flying our technologies'. She led the flight implementation and delivery of the Phoenix/MECA Wet Chemistry Laboratory.

MICHAEL HECHT | PROFESSOR, MIT 1982

A physicist at JPL, Dr. Hecht graduated from Stanford University in 1982 with a PhD in applied physics. He worked on semiconductor surface and interface science, planetary science, micro electromechanical systems (MEMS), and scientific instrument development. He left JPL in 2012 to become Assistant Director for Research Management at the MIT Haystack Observatory. He is principal investigator of the Mars Oxygen ISRU Experiment (MOXIE), an exploration technology investigation, which NASA selected in 2014 to fly on the Mars 2020 mission.

WILLIAM JOSEPH KAISER | PROFESSOR, UCLA 1986

Dr. Kaiser is the director of Actuated Sensing & Coordinated Embedded Networked Technologies research group and co-director of the UCLA Wireless Health Institute. He worked at JPL from 1986 to 1994, where he developed and demonstrated the first electron tunnel sensors for acceleration and infrared detection and initiated the NASA/JPL microinstrument program. Dr. Kaiser is a winner of the 2007 Gold Shield Prize and has been a Fellow of American Vacuum Society since 1994. He has received the Allied Signal Faculty Research Award, the Peter Mark Award of the American Vacuum Society, the NASA Medal for Exceptional Scientific Achievement, the Arch Colwell Best Paper Award of the Society of Automotive Engineers, and two R&D 100 Awards. In 2019, he became an elected Fellow of IEEE.

CONTRIBUTORS

ERIC R. FOSSUM | PROFESSOR, DARTMOUTH COLLEGE 1990

Dr. Fossum is Associate Provost in the Office of Entrepreneurship and Technology Transfer (OETT), Director of the PhD Innovation Program at the Thayer School of Engineering, and the John H. Krehbiel Senior Professor for Emerging Technologies at Dartmouth College. He joined JPL in 1990, where he invented the camera-on-a-chip technology for which he is best known. He has published over 300 technical papers and holds 165 patents. Dr. Fossum has won numerous awards for his work, including the NASA Exceptional Achievement Medal, the NSF Presidential Young Investigator Award, and the Queen Elizabeth Prize. Nearly all the five billion CMOS cameras made each year use his intra-pixel charge transfer invention. He received his PhD in engineering and applied science (EE) from Yale University in 1984.

ROBERT FATHAUER | ARTIST 1987

In 1987, Dr. Fathauer joined the research staff of JPL. Long a fan of M.C. Escher, Dr. Fathauer began designing his own tessellations with lifelike motifs in the late 1980s. He learned printmaking techniques to produce limited-edition screen prints and woodcuts of his tessellation designs. In 1993, he founded a business, Tessellations, to produce puzzles based on his designs. Over time, Tessellations' product line has grown to include mathematics manipulatives, classroom posters, and books. More recently, he has been working with ceramics to create sculptures that combine fractal character with hyperbolic geometry. These abstract sculptural forms are inspired by natural structure found in corals and plants.

BARBARA WILSON | RETIRED 1988

Dr. Wilson joined JPL in 1988 as technical group supervisor of the Microdevices Section. Shortly thereafter, she was named manager of MDL. She retired from JPL in 2011 as its Chief Technologist. 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.

ANDERS LARSSON | PROFESSOR, CHALMERS UNIVERSITY 1988

From 1984 to 1985, Dr. Larsson worked in the Department of Applied Physics at Caltech, and from 1988 to 1991, he worked at JPL. He has been a Guest Professor at Ulm University (Germany), at the Optical Science Center, University of Arizona at Tucson (USA), at Osaka University (Japan), and at the Institute of Semiconductors, Chinese Academy of Sciences (China). He has published more than 500 scientific journal and conference papers, as well as two book chapters. He was a Member of the IEEE Photonics Society Board of Governors (2014–2016), an Associate Editor for the Journal of Lightwave Technology (2011–2016) and is a Member of the Editorial Board of IET Optoelectronics. His scientific background is in optoelectronic materials and devices for optical communication, information processing, and sensing. He is a Fellow of the Optical Society of America and EOS.

ROBERT J. LANG | ORIGAMI EXPERT 1988

Dr. Lang began work at MDL in 1988. He studied the mathematics of origami and used computers to study the theories behind origami, and he is one of the foremost origami artists and theorists in the world. He is known for his complex and elegant designs, most notably of insects and animals. He has made great advances in real-world applications of origami to engineering problems. Dr. Lang has authored or co-authored over 80 publications on semiconductor lasers, optics, and integrated optoelectronics, and he holds 46 patents in these fields. In 2001, Dr. Lang left engineering to be a full-time origami artist and consultant. However, he still maintains ties to his physics background: he was the editor-in-chief of the IEEE Journal of Quantum Electronics from 2007 to 2010. He holds a PhD in applied physics from Caltech.

TOM KENNY | PROFESSOR, STANFORD UNIVERSITY 1989

Dr. Kenny is currently the Richard W. Weiland Professor of Mechanical Engineering at Stanford. His group researches fundamental issues in and applications of micromechanical structures. These devices are usually fabricated from silicon wafers using integrated circuit fabrication tools. Because this field is multidisciplinary, work in Dr. Kenny's group includes strong collaborations with other departments, as well as local industry. Dr. Kenny worked at JPL from 1989 to 1993, where his research focused on the development of electron-tunneling high-resolution microsensors.

JPL & MDL collective success

Since their inception, CSMT, and later MDL, have been nurtured and supported by the JPL Director, while the MDL Director and Deputy Director have ensured that MDL's research, technology and products uniquely add value to JPL's output in support of tasks for NASA.

JPL DIRECTORS

Lew Allen, Jr.
1982 – 1990

Dr. Allen attended West Point and earned a PhD in physics from the University of Illinois. During his military career (1945-1982), he attained the rank of General and a position as Air Force Chief of Staff, served as director of the National Security Agency (NSA), and was a leading expert in the military space program. Most of the work he did during these years was heavily classified. He came to JPL as Director in 1982 and retired in 1990.

Edward Stone
1991 – 2001

Dr. Stone's research specialty was cosmic radiation, whose existence was known from the beginning of the 20th century but was poorly understood. In 1972, JPL's Bud Schurmeier, project manager for the Mariner-Jupiter-Saturn 1977 mission, later named Voyager, invited Stone to become the mission's project scientist. His decade as JPL Director was tumultuous. He became Director just as officials at NASA headquarters began to balk at the high cost and slow pace of planetary missions.

Charles Elachi
2001 – 2016

In the spring of 1970, Dr. Elachi interviewed for a summer job with Walter E. Brown Jr. at JPL. Brown, head of JPL's Radar Section, introduced Elachi to what turned out to be his life's work. Brown put Elachi to work on a proposal to send an imaging radar instrument to Venus to map beneath the planet's permanent cloud cover. This work became the Venus Orbiting Imaging Radar proposal and, after a long evolution, the Magellan mission.

Michael M. Watkins
2016 – Present

Dr. Watkins became Director of JPL on July 1, 2016. In this role, he also serves as a vice president of Caltech, which staffs and manages JPL for NASA. He was project scientist for the GRACE, GRAIL and GRACE Follow-On missions. He is also a pioneer in development and use of gravity data for new science applications to better understand Earth's climate and evolution. His other research interests include mission design, instrument design and science analysis for acquisition and use of remote sensing data for Earth and other planets.

MDL DIRECTORS

JPL Director Dr. Charles Elachi appointed MDL's first Director when MDL was reorganized in 2007. He and the subsequent JPL Director, Dr. Mike Watkins, have chosen eminent researchers to act as Director, all supported by the same, very capable Deputy Director.

Jonas Zmuidzinas
2007 – 2011

For the nearly three decades he has been at Caltech, Dr. Zmuidzinas has provided the vision and support that continue to secure MDL's prominence. He ensures that MDL works on creative new technologies for NASA and other government agencies. He laid the foundation of MDL's Superconducting Devices and Materials Group, and he continues to be a source of ideas for truly novel technologies.

Christopher R. Webster
2011 – 2017

Dr. Webster is a JPL Fellow and Senior Research Scientist who also formerly served as the Program Manager of the Planetary Science Instruments Office. He has developed and built innovative miniature instruments for planetary missions to Mars, Venus and Titan and is the institutional principal investigator on the Tunable Laser Spectrometer (TLS) instrument in the SAM analytical suite on the Curiosity Rover now operating on Mars.

Robert Green
2017 – Present

Dr. Green is a JPL Fellow and Senior Research Scientist and is the Principal Investigator of the Earth Surface Mineral Dust Source Investigation (EMIT). In 2018, EMIT was selected by NASA to fly on the International Space Station. He is also a Senior Research Scientist at JPL, Caltech. For more than 25 years, his research has used advanced imaging spectrometer instrumentation to test hypotheses and pursue science investigations on Earth, Mars, the Moon, and throughout the solar system.

MDL DEPUTY DIRECTORS

There has only been one Deputy Director of MDL; he has worked with all three Directors.

Siamak Forouhar
2007 – Present

Dr. Forouhar pioneered semiconductor laser development at JPL three decades ago. He created JPL's semiconductor laser capability, which has seen infusion into a wide variety of flight projects in Earth and planetary science. He has received several NASA Exceptional Engineering Achievement Awards and the Jet Propulsion Laboratory Exceptional Technical Excellence Award. He holds eight patents and has published more than 70 articles in refereed journals.

As the MDL deputy director, Dr. Forouhar has made significant contributions to determining MDL's long-term strategic direction, in line with JPL's strategic plans. He serves as a primary contact between MDL and JPL senior management, Caltech faculty, and other universities.

MDL abiding stars

The combination of the leadership, vision, and innovation of many dedicated and talented individuals at MDL, both past and present, has resulted in numerous achievements that are impressive in their scope, significance, and ingenuity.

Chuck Manning
September 9, 1980

1980
ENGINEERING TECHNICAL SPECIALIST

Mr. Manning, an original member of the MDL Support Group, implements many of MDL's general use fabrication capabilities. He works with MDL users and equipment manufacturers to develop specifications and implement new semiconductor fabrication processes and equipment, working towards the never-ending need to modernize MDL's capabilities. The work often entails equipment installations requiring large modifications to the building, including increased cleanroom space and upgrades to the facilities that service the increasingly complex requirements of a modern semiconductor "fab". He has led JPL public outreach efforts, e.g., Send Your Name to Mars and public open house events, and produced technology publications.

Henry G. Leduc
July 7, 1981

1981
MICRODEVICES ENGINEER

Dr. Leduc, a Senior Research Scientist, started at JPL in 1981 as an intern, then a postdoc and employee. He has worked on superconducting materials, devices, sensors, focal plane arrays, and instruments for astrophysics, Earth and planetary observations. Over 20 years ago, he started working on other superconducting detectors, including TES detectors and SQUIDs. He was involved with kinetic-inductance-based readout for superconducting pair-breaking detectors from their beginning, and most of his work over the last 15 years focuses on devices based on the kinetic inductance effect, along with materials development and fabrication of those devices.

John K. Liu
February 13, 1985

1985
SENIOR ENGINEER

Mr. Liu received his BS in Engineering Science, Bioengineering from UC San Diego in 1984 and his MSEE from California State University, LA, in 1986. From 1985 to 1989, he worked at JPL on solar cell and III-V MBE growth. From 1989 to 1991, he worked at TRW on III-V thin film growth using MBE for MMIC applications. After that, he worked on the development of Quantum Well Infrared Photodetector (QWIP) cameras at JPL. His current interest is in developing a set of reliable and reproducible microfabrication techniques in support of MDL technologies.

Douglas Bell
November 17, 1986

1986
TECHNOLOGIST

Dr. Bell first came to JPL as a postdoc in 1986 and was designated a Senior Research Scientist in 2009. He develops detectors based on novel materials and novel effects, such as wide bandgap semiconductors, shape-engineered tunnel barriers, nanocrystal storage elements, and nanostructured metamaterials. He conducts nanoscale electronic and structural characterization of materials and devices using scanning probe methods. His work is supported by both NASA and non-NASA sponsors.

Richard Muller
July 11, 1988

1988
MICRODEVICES ENGINEER

Mr. Muller joined JPL in 1988 to run its first electron beam (e-beam) lithography system, and he is currently in charge of operating MDL's JEOL JBX 9500FS e-beam lithography system and its associated tools. During his 29 years at JPL, he has operated three e-beam tools and has contributed to the development and delivery of many optical and electronic components for research and flight projects.

Bruce Bumble
March 6, 1989

1989
SUPERCONDUCTING MATERIALS & DEVICES ENGINEER

Dr. Bumble's early work involved development of SIS and HEB mixers for THz Radio Astronomy on the Herschel Space Telescope. Today, in collaboration with UCSB, he improves MKID devices for UV, optical, and near IR telescope cameras; TES bolometers for mm wave spectrometers; quantum computing devices; and SNSPD detectors. In 1989, Dr. Bumble joined MDL as a Member of the Technical Staff, where he still works on superconducting materials and devices, mainly for astronomy applications.

James L. Lamb
February 27, 1984

1984
MDL MANAGER

Mr. Lamb is 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 at this state-of the-art semiconductor device processing facility. He has facilitated 30 years of affordable, safe, productive MDL operations. For his contributions, he received two NASA Exceptional Service Medals (1995 and 2011) "in recognition of exemplary management of the technical infrastructure support to the Jet Propulsion Laboratory's Microdevices Laboratory." A physicist and JPL employee since 1984, he has been associated with MDL operations since MDL's inception.

Siamak Forouhar
September 28, 1986

1986
MDL DEPUTY DIRECTOR

Dr. Forouhar started as a Member of the Technical Staff, became a Group Supervisor in 1996, and became Deputy Section Manager in 2003. Through his personal leadership, innovation, unique expertise and research excellence, he has developed a strong research group and has created and grown MDL's semiconductor laser capability. These projects are a highlight of JPL's capability and success.

Toney Davis
October 29, 1987

1987
ENGINEERING DEVELOPMENT TECHNICIAN

Mr. Davis has supported MDL since its construction in 1987, first as a contractor and then as a JPL employee. He is formally trained as a cleanroom maintenance technician. He has sustained all MDL cleanroom cleanliness levels, including certified ISO 4 (class 10) processing areas. His expertise in the cleaning of surfaces has allowed him to clean equipment for installation and use in the facility, as well as decontaminate equipment after servicing and for removal from the facility – key contributions due to the acutely hazardous and toxic materials used in MDL operations. Toney also processes centralized waste for the facility and is a backup for both oversight of the MDL Safety Monitoring systems and for Building Facilities support.

KEEPERS

> "The diverse staff has outstanding expertise, and their passion for the work was clearly evident."
>
> —The Visiting Committee, September 5-6, 2019

DR. THOMAS L. KOCH
Committee Chair
Dean of College of Optical Sciences and Professor of Optical Sciences, University of Arizona

DR. BARBARA WILSON
Committee Co-Chair
Retired Chief Technologist, Jet Propulsion Laboratory

DR. EUSTACE DERENIAK
Former Chair (2008–2015)
Professor Emeritus of Optical Sciences and Electrical and Computer Engineering, University of Arizona

DR. ERIC R. FOSSUM
John H. Krehbiel Sr. Professor for Emerging Technologies, Director, PhD Innovation Program, Thayer School of Engineering and Associate Provost for Entrepreneurship and Technology Transfer, Dartmouth College

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

DR. DEBORAH CRAWFORD
Vice President for Research, George Mason University

DR. JED HARRISON
Department Chair and Professor of Chemistry, University of Alberta

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

DR. PAMELA S. MILLAR
Program Director, NASA Earth Science Technology Office (ESTO)

DR. NAI-CHANG YEH
Professor of Physics, Fletcher Jones Foundation Co-Director, Kavli Nanoscience Institute, California Institute of Technology

DR. SUSAN M. LUNTE
Ralph N. Adams Distinguished Professor of Chemistry and Pharmaceutical Chemistry, Director, Adams Institute for Bioanalytical Chemistry, University of Kansas

DR. ROBERT WESTERVELT
Director of the NSF Science and Technology Center for Integrated Quantum Materials and Mallinckrodt Professor of Applied Physics and of Physics, Harvard University

DR. VENKATESH NARAYANAMURTI
Benjamin Peirce and Research Professor of Technology and Public Policy, Harvard University

DR. GREGORY KOVACS
Chief Technology Officer at SRI International in Menlo Park, CA., Professor Emeritus of Electrical Engineering with a courtesy appointment in the Department of Medicine, Stanford University

MR. GEORGE KOMAR
Retired Associate Director in the NASA Earth Science Division and Program Manager, NASA Earth Science Technology Office (ESTO)

DR. OSKAR PAINTER
John G Braun Professor of Applied Physics and Physics, Fletcher Jones Foundation Co-Director of the Kavli Nanoscience Institute, California Institute of Technology

DR. ALBERT P. PISANO
Dean of the Jacobs School of Engineering, Walter J. Zable Chair in Engineering, Professor of mechanical, aerospace, electrical and computer engineering, University of California, San Diego

DR. DAVID SANDISON
Director of the Center for Microsystems Science, Technology & Components, Sandia National Laboratories

DR. AXEL SCHERER
Neches Professor of Electrical Engineering, Applied Physics and Physics, California Institute of Technology and Director of the Caltech Global Health Initiative

> "The majority of R&D within MDL is leading the field, producing exciting results, enabling new science, and is well aligned with the stated MDL and JPL objectives."
>
> —The Visiting Committee, September 5-6, 2019

MDL Visiting Committee

The Visiting Committee was initiated shortly after MDL's reorganization in 2007. Its membership comprises individuals with an enormous range of skills and experience. The committee's remit is not only to review past and current activities and plans but also to be proactive in giving advice.

The Committee comes to MDL every two years and then produces a formal report, most recently in 2019. As with previous visits, their insights have proven very valuable and are much appreciated. MDL management listened to and is acting on their recommendations, which are taken very seriously.

Unusual routes to success

Occasionally, despite careful planning and meticulous work, things don't turn out as expected. Some of these events are not the result of anything that happened at MDL. On other occasions, a project is unsuccessful or ends earlier than expected. These incidents can be viewed constructively: the work is not wasted, just postponed.

Artist's impression of the Phoenix spacecraft, which landed near the northern polar ice cap of Mars in 2008.

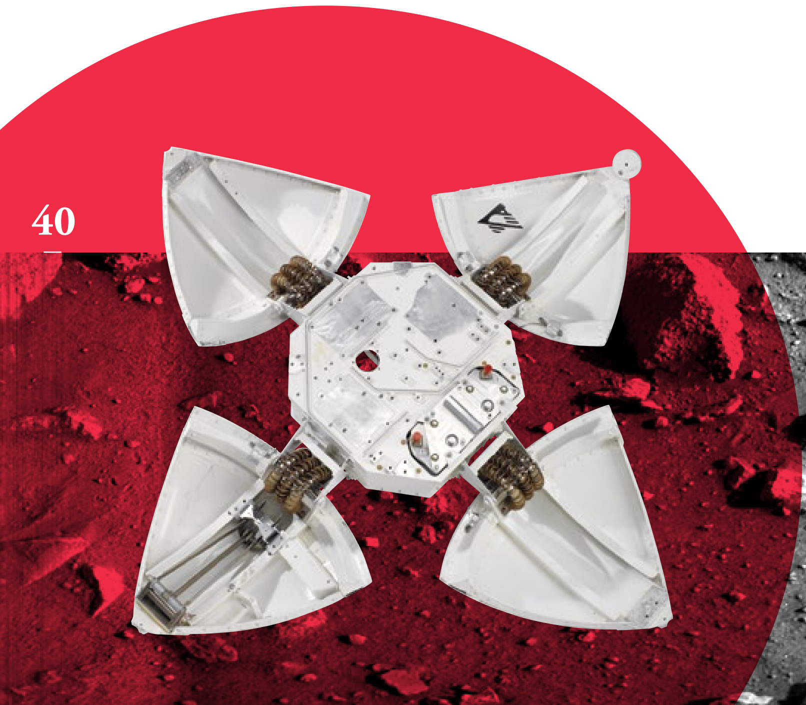
RECYCLING

MOx

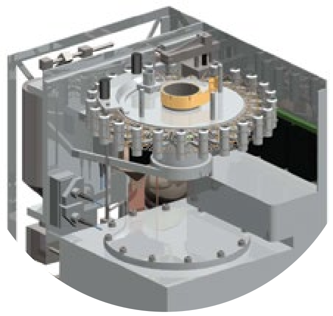
The history of Mars exploration features many notable successes but also some failures. The NASA Viking project launched two landers and two orbiters in 1975 and was the first mission to land a spacecraft safely on another planet's surface. NASA sent no successful landers toward Mars for many years. However, in the early 1990s, from within the new MDL building, Dr. Frank Grunthaner saw an opportunity. Dr. Grunthaner had become enamored with the possibilities of silicon as a mechanical material and took his ideas to Dr. Bruce Murray at Caltech. Together, they developed a silicon-based instrument with a mass of less than 850 g, complete with its own power supply, to be flown on the 1994 Russian Mars Lander mission. The device, called the Mars Oxidation experiment (MOx), was developed in collaboration with scientists at Sandia National Laboratory. It was a sensor array to measure the oxidation potential of the Martian soil and was to be placed in the Martian soil or exposed to the Martian atmosphere. The Russian Surface Lander was scheduled to launch in 1994 but was delayed for two years. Then, as the rocket finally launched to take the probe out of earth's orbit, it misfired, and MOx, along with all the other instruments on board, landed in or near the Pacific Ocean off South America.

Although MOx was physically lost, its concept lived on. Not long after the failed launch, Dr. Grunthaner began what would become a long-standing collaboration with Dr. Jeffrey Bada of UCSD to develop a much more capable system to search for life on Mars. The instrument, called Urey, comprised a complex microfluidic wet chemistry unit and an upgraded version of the MOx concept. In 2007, NASA selected Urey as a contribution to the European Space Agency's ExoMars mission. But the story did not end there; the "Urey" section opposite has the conclusion.

Probe, Mars 96 with Mars Oxidation Experiment.



This is the first photograph ever taken on the surface of the planet Mars. It was obtained by Viking 1 just minutes after the spacecraft landed successfully on July 20, 1976.



Urey Mars Organic and Oxidant Detector.

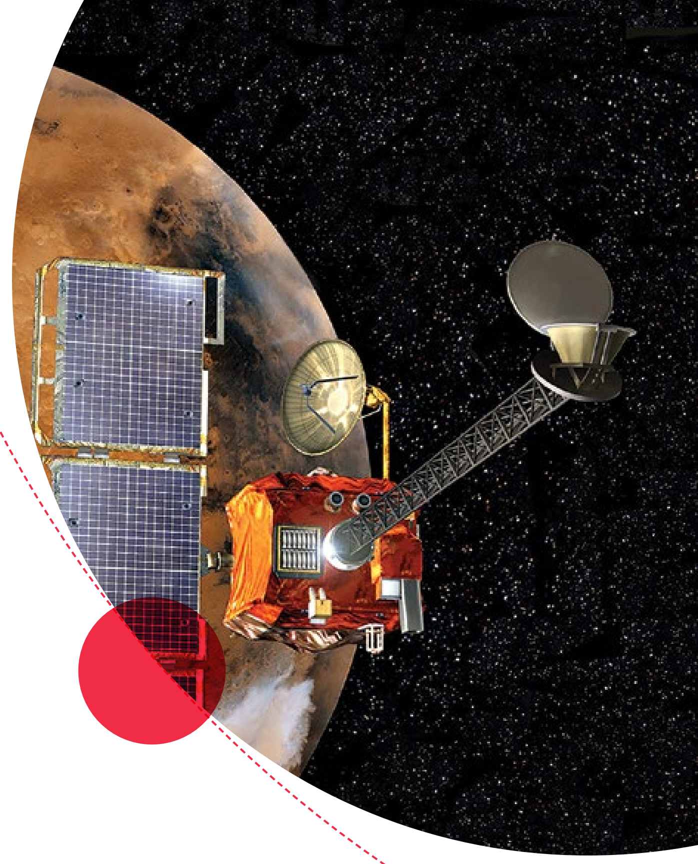
UREY

In addition to the MOx sensor developed previously, the Urey instrument included remarkable MDL technological advances. The instrument was named after Harold Urey, winner of the Nobel Prize in Chemistry in 1934, who had pioneered research on the origin of life. The instrument was developed in MDL in collaboration with Drs. Jeff Bada (UCSD) and Rich Mathies (UC Berkeley). The team rapidly realized that in addition to the solid-state MOx device, Urey would need methods for analyzing very, very low concentrations of amino acids, the building blocks of proteins and one of the most compelling signatures of life. There were many challenges to overcome in developing these methods, and two of the biggest were extracting amino acids from samples of Martian soil or rock and then analyzing them. The team set a goal of using MDL's capabilities in lithography, chemical and plasma etching, thin-film deposition and wafer bonding to develop a 6-inch-diameter device that could operate with the functionality of a fully equipped terrestrial lab. At that time, MDL was developing instrument concepts and demonstrating amino acid separation using capillary electrophoresis in deeply patterned SiO_2 wafers. This was the Microfluidic Lab-on-a-Chip.

Another key problem was how to strip amino acids out of a soil matrix and put them into solution. Amino acids range from highly hydrophobic (oily or water repellant) to rather hydrophilic (water soluble), posing a challenge to getting all amino acid types into an aqueous solution. Water's ability to dissolve various materials is a strong function of temperature. The novel approach developed, sub-critical water extraction, uses water at a range of temperatures (up to 350°C) and pressures to dissolve all target amino acids.

At the same time, the European Space Agency (ESA) was planning a major mission to Mars, ExoMars, that would include a rover and many instruments. NASA was a partner in the enterprise, and in January 2007, it selected Urey as one of the instruments it would contribute to the mission. Unfortunately, ESA suffered several financial setbacks and was forced to postpone the launch date. NASA reviewed ESA's plans and its commitments, and in July 2009, Urey was canceled.

Yet again, although the opportunity to be part of the mission was lost, the technology lived on. Some of the concepts developed for Urey have been continuously refined and evolved since then and are now a part of the OWLS project, looking for life not on Mars but in the ocean worlds of the outer planets (see page 66).



The Mars Surveyor 2001 project was a multi-part Mars exploration mission intended as a follow-up to Mars Surveyor '98. After the two probes of the 1998 project, Mars Climate Orbiter and Mars Polar Lander, were both lost, NASA's "better, faster, cheaper" exploration philosophy was re-evaluated, with a particular eye on the two 2001 project probes.

MECA and MECA

In the 1990s, MDL started producing an instrument for the lander payload of the Mars Surveyor 2001 mission, which also included an orbiter. The Mars Environmental Compatibility Assessment (MECA) was designed to test if dust in the Martian soil might be hazardous. MECA was to run in situ tests using several different instruments produced in collaboration with many different institutions. It included optical and atomic force microscopes and a wet chemistry lab unit that mixed Martian soil with water and analyzed the resulting solution. The instrument was completed and tested satisfactorily. Unfortunately, in the late 1990s, two Mars missions failed, the Surveyor lander mission was canceled, and only the orbiter, then renamed 2001 Mars Odyssey, was launched. However, the work that had been invested in developing the instrument was not wasted.

The complete instrument was mothballed with the cancellation of the mission. However, it was later resurrected with the same acronym, MECA, but now meaning Microscopy, Electrochemistry, and Conductivity Analyzer. MECA was adapted for the successful Phoenix mission to Mars that launched in 2007. The unit performed well on Mars and made many discoveries, but the most remarkable was the presence of perchlorate on the Martian surface. This finding revolutionized our understanding of the surface of Mars and the ability to detect organic matter there, including the need to re-examine the findings of the Viking missions.

Creating the lab of the future

MDL was born 30 years ago but has been updated continuously ever since; its facilities and equipment remain state of the art, and its staff is renewed with new and diverse minds, as well.

MDL is dedicated to and has cultivated an environment that values and promotes diversity, leadership, vision, and innovation. By fostering a community in which one can interact with people with different backgrounds, interests, and expertise, unexpected inspirations become a way of life. JPL excels at bringing experts together to create an environment where new ideas can evolve into useful technologies, and MDL exemplifies this spirit of collaboration.

Artwork submitted for the cover of the journal Analytical Methods, when an article on measuring silver (Ag) used to sterilize drinking water was accepted for publication. It visually summarizes the method and its potential for future human spaceflight.

Team members Fernanda Mora and Jessica Creamer performing final assembly and inspection of the Chemical Laptop analyzer upper stage.

DIVERSITY

OUTREACH

Talking to a larger audience

NASA encourages public outreach, and unsurprisingly, MDL scientists and technologists attract media attention. The examples here show part of that effort.

FLORIAN KEHL

Florian, a native of Switzerland, has been a space enthusiast since his early childhood and he gave presentations about JPL's Mars rovers when he was in elementary school. He still loves to motivate the next generation of explorers to follow their dreams and to share his passion for spaceflight with the public. He was invited to several public events, most recently as a keynote speaker in San Francisco and at his alma mater in Switzerland.

In his home country, he was featured in several magazines, newspapers, television programs, and a radio broadcast series, reaching millions of people. He also engaged with the public through a guest article and through his involvement as an independent rocketry consultant for CBS's "Strange Angel," a series about the life of Jack Parsons, one of the founders of JPL. The group simulated Mars missions in the Chilean Atacama Desert, where novel life-detection instruments were tested on a rover in a relevant environment. These simulations were featured by media around the globe, from Chile to Vietnam.

Since his childhood dream came true, Dr. Kehl regards it as his duty to share the wonders of space exploration with the world.

FERNANDA MORA

In 2012, Dr. Mora was interviewed about her work by the largest newspaper in Cordoba, Argentina, where she grew up. She reached a wide audience, and it was especially important for the people of her hometown, Saldan. The news spread quickly in this small community, where most people know each other. Soon, Dr. Mora was contacted by the elementary school in Saldan and invited to talk to the students. In 2018, she was invited to give a TEDx presentation there. The event had more than 1600 people in attendance and 70,000 following via live streaming. The presentation was titled: "*El desafío de buscar vida extraterrestre*" ("The challenge of looking for extraterrestrial life"). During that week, she also visited three high schools to chat with the students about her experience working at JPL. She was also interviewed by two radio stations, a newspaper and a magazine. "I was terrified about being on the stage in front of so many people, but at the end it was a wonderful experience. As a scientist, I felt very honored to have the opportunity to reach such an audience. But more importantly, as a woman, I felt a huge responsibility: I wanted to be an example for girls and young women, to show them that they can do whatever they set their mind to. I wanted them to know that there are no limits if you persevere and are willing to make sacrifices. I believe if I got at least one person inspired by my talk, it was all worth it."

Last year, an Argentinian news station interviewed Dr. Mora and two other Argentinians working at JPL. The interview aired on one of the main TV stations in Argentina and was also converted to a podcast format.

DIVERSITY

Innovating from the get go

Some MDL technologists and scientists arrive and quickly make their mark with a truly original approach or product.


JESSICA


ERIC


EMMA


ROGER


SOFIA


MATHIEU


FERNANDA

JESSICA CREAMER

Would you believe that someone who got the lowest possible score on the AP chemistry test in high school could later become a star research chemist at JPL? Jessica started her undergraduate degree at Northern Arizona University without having chosen a major. Taking her AP chemistry experience as a challenge rather than a defeat, she took Chemistry 101 in her freshman year. This time, the subject clicked, so she majored in chemistry and went on to earn both a masters and PhD in pharmaceutical chemistry from the University of Kansas. Chemistry truly suited Jessica; after coming to JPL as a postdoc, she completed a project that led to a publication in the journal Analytical Chemistry. That publication was featured as the American Chemical Society Editor's Choice, and the work also led to her winning the Outstanding JPL Postdoc Research award two years in a row. Jessica identifies Jani Ingram, her undergraduate advisor, and Sue Lunte, her PhD advisor, as her two biggest inspirations and mentors. She says, "Both are hardworking, intelligent, and passionate woman that taught me a lot about science and life." Jessica's job is primarily research and development for an instrument suite called OWLS, which is being developed to look for life in the ocean worlds of the outer solar system. She spends much of her day in the lab setting up experiments or at her desk analyzing results. Her work will help the team decide how to build and operate their portable prototype instruments, which will define the design of a final instrument suite for a future mission.

ROGER O'BRIENT

Roger was set on his path to JPL by an esoteric mixture of Mr. Wizard and learning about the Manhattan Project before he was even a teenager. In some respects, his path was conventional: he received a BS in physics from Caltech followed by a PhD from UC Berkeley's Physics Department. At JPL, Roger designs, tests, and fields cryogenic detectors. He and others took a calculated risk and attempted to develop a new cryogenic detector, defying conventional wisdom that suggested it would not work. However, the sensor they developed, a thermal kinetic inductance detector (TKID), did work. Roger still remembers the day when the team finally got their testbed device working very well after a small adjustment and found that the noise level dropped to an unimaginably low level. In fact, what they had developed was a working solution to many problems in the field. To quote Roger, "That sort of serendipity is magic." Roger's experiences, starting with those of his childhood, have made him realize that physicists are modern-day wizards.

ERIC KITTLAUS

Eric has always been very curious about the natural world and how things work. When he was about five, he saw the moon and planets through a telescope for the first time. This experience kindled his lifelong fascination with space. After earning a bachelor's in physics and mathematics at Santa Clara University, he went on to receive a PhD in applied physics at Yale. While finishing his PhD and wondering what to do next, Eric saw an announcement on the JPL website advertising a postdoctoral position. The position offers a great deal of freedom and autonomy and allows him to focus on developing completely new technologies that will be useful for NASA applications in the coming decades. He is developing devices that use electrically driven sound waves to control the behavior of light on the surface of a silicon chip. This technology could enable many new functionalities for signal processing to novel light sources. It could even raise the possibility of something never before done on the chip scale: making an optical diode. Eric has also been working on an approach to generate low-noise microwaves by combining lasers. This led to that most satisfying moment for any scientist: seeing your research product perform satisfactorily. In this case, Eric's device ran successfully in a field test of a JPL-built radar that detects clouds and rain.

EMMA WOLLMAN

While growing up, Emma was interested in a wide range of subjects, from science to the arts, and she was unsure which field to pursue. Influenced by the great physics teachers she had in high school, she went to Swarthmore College and majored in physics and minored in ancient Greek, reflecting the diversity of her interests. Emma came to JPL from Caltech as a postdoc to develop UV single-photon detectors. She has continued in the same field, working on detectors for the Deep Space Optical Communication project to be demonstrated on the Psyche mission. She characterizes these detectors and integrates them into the ground receiver that will be located at Palomar Observatory's 5 m Hale Telescope. She finds great satisfaction in making a device that performs better than expected at the first attempt and then finding that her model's predictions match the measurements she has taken. Emma greatly enjoys volunteering one weekend each year when JPL is open to the public, stating, "It's fun to try and explain my job to people from such diverse backgrounds." This philosophy is a reflection of her own development as a scientist. When asked what she would say to someone wanting to follow a career like hers, she emphasized the need to pay attention to one's life outside of science and math, no doubt because she draws on many of her non-STEM skills for her job.

MATHIEU FRADET

For as long as he can remember, Mathieu has always been attracted to science because it allows us to understand and explain the world around us. He was particularly interested in math, as math was the key to understanding physics. Not surprisingly, then, both his undergraduate and graduate degrees are in physics. While he was a graduate student at the University of Montréal, he applied successfully for an internship at JPL. The three-month internship turned into six months, and six months turned into a permanent position after he graduated. His job at JPL is mainly focused on semiconductor lasers, spanning from their characterization to their implementation on instruments for spaceflight. He assembled a semiconductor laser-based gas sensor that can identify six different species. This sensor will be used to detect combustion products during tests as part of the SAFFIRE project, which focuses on spacecraft fires. The results will help us understand the risks to human health posed by these fires and develop fire mitigation strategies.

SOFIA RAHIMINEJAD

Sofia's road to JPL started when she was 14 and became interested in technology through an after-school activity called "Technology for Girls." This imaginative program included weekly visits to large companies like Volvo and Ericsson. At these companies, the participants would meet female engineers, who explained what they did. According to Sofia, "I joined for the free cookies but realized soon this was something I wanted to do." Sofia went on to study engineering physics at Chalmers University of Technology in Sweden and achieved a double masters in nano-science and technology before completing her PhD in "Micromachining of high frequency components." Sofia learned about JPL when she met a friend at a conference who, in turn, had a friend who worked at JPL. Sofia came to Caltech at the end of September 2017 with three bags and five days to find an apartment. She did not know what to expect from Pasadena or JPL, where she would undertake her postdoctoral work. Before arriving, she had an idea about developing a MEMS rotating switch. After much hard work to model, fabricate and test the device, Sofia experienced a magic moment she will never forget: she saw her switch actually move. She presented her work to a larger audience and was rewarded by winning a JPL Best Postdoc Poster award. Sofia found an apartment only three days after arriving in Pasadena, but more importantly, she has thoroughly integrated into the Caltech and JPL communities.

FERNANDA MORA

Fernanda was born and raised in a small town in Córdoba Province, Argentina, and has been fascinated by science since childhood. She moved to the United States in 2005 to pursue her graduate studies and received her PhD in chemistry in 2009. She then began looking for postdoctoral positions and saw an ad for a position at JPL. Thinking that the spot was only available to US citizens, Fernanda did not read the ad further, but the next day, the same ad appeared again. She saw it as a sign to explore JPL opportunities and found a posting for a microfluidics position. She had the exact background required, and soon after, she joined JPL as a postdoctoral scholar. Her postdoctoral work focused on developing a fully integrated microfluidic device capable of performing automated analyses of amino acids for use in spaceflight. Her research since then has generally focused on developing new strategies for using capillary electrophoresis (CE) and microchip electrophoresis (ME) to analyze inorganic and organic molecules. Her current work involves developing strategies for simultaneous analysis of inorganic ions and organic acids via ME and contactless conductivity detection, as well as analysis of organic biosignatures by CE and mass spectrometry. Fernanda enjoys sharing her work with others, including her own family: she was proud to take her brother and his friends on a tour of JPL. Fernanda says of their visit, "The whole group was so fascinated with everything they saw that it made me value my work even more!" In 2019, Fernanda was a co-recipient of JPL's Lew Allen Award in recognition of "excellence in the development and validation of chemical analysis methodology and electrophoresis instruments for future life detection missions."

To boldly go

Each member of the teams making up the MDL workforce knows their plan for the present and the near future. However, each group also shares a common vision of where they will jointly go in the more distant future.

MDL's leadership, vision, and innovation are illuminated in its rise to the challenge of JPL and NASA missions through its contributions of core competencies.

New JEOL JBX 9500FS e-beam lithography system.

E-beam lithography & diffractive optics

E-Beam technologies are at the core of MDL and include state-of-the-art nanolithography and development of new techniques to fabricate unique components for many JPL instruments in areas including optics, electronics, and micro-mechanics, with applications from Earth science to astronomy.

For over three decades, electron-beam lithography has been an enabling technology for MDL. The MDL team has provided MDL users 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. MDL developed unique analog e-beam techniques for creating grayscale surface-relief structures in a variety of polymers, dielectrics, metals, and semiconductors. This allowed creation of nearly arbitrary transmissive and reflective diffractive optics such as blazed gratings, lenses, and computer-generated holograms, for wavelengths ranging from ultraviolet to long-wave infrared. More importantly, MDL developed methods for fabricating these grayscale surfaces on non-flat (convex/concave) substrates with up to ten millimeters of height variation. This necessitated development of custom e-beam calibration techniques, substrate mounting fixtures, and pattern preparation software.

The processes for fabricating binary nanoscale structures are continually evolved and utilize both metal lift-off and plasma etching to realize functional devices. Precise patterns can be fabricated on tiny pieces of novel semiconductor materials as well as on very large optical substrates up to 230 mm square. Combining MDL precision lithography with micro-mechanical silicon etching processes produces slits and shaped apertures with unmatched accuracy and uniformity. These precise silicon apertures are frequently made extremely black using a special cryo-etching process, making them ideal for many optical instruments.

The Mars 2020 Mission will examine sand-grain size samples for signs of life, past or present.

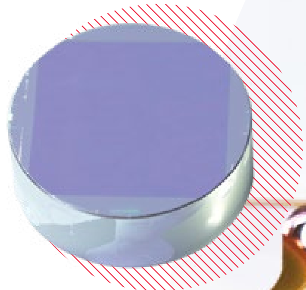
PIXL instrument engineering model in test.

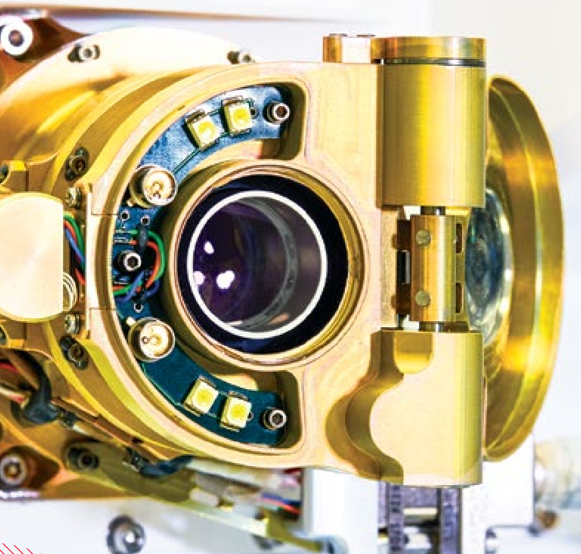
The capability of MDL to fabricate diffractive optics on convex and concave substrates and blackened precision slits has enabled JPL to design, build, and fly extremely high-performance imaging spectrometers for many airborne and spaceborne missions. These spectrometers, require custom designed and fabricated gratings with precisely shaped grooves that produce tailored spectral efficiency over multiple octaves in wavelength, allowing equalized signal-to-noise spectral imaging. Prior to delivery, the performance of the optics is measured at MDL, and this capability has helped greatly over the years to optimize the spectral efficiency, scatter, and wavefront error characteristics of our components. Over the years, we have delivered gratings and/or slits for the following spaceborne spectrometers: Hyperion (Earth Observing-1), CRISM (Mars Reconnaissance Orbiter), ARTEMIS (TacSat-3), Moon Mineralogy Mapper (Chandrayaan-1), and airborne spectrometers: AVIRIS-NG, CAO, NEON, HyTES, PRISM, and UCIS. We have also recently fabricated and delivered optical components for instruments on the Mars 2020 rover, Perseverance: an ultraviolet grating for SHERLOC and two spot-array generating diffractive optics for PIXL.

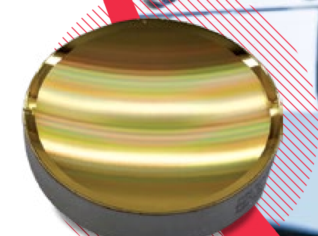
The MDL team is constantly challenged by our JPL science and instrument colleagues to fabricate ever more difficult components with higher performance. Our current and near-future work is focused on developing fabrication processes for our largest ever concave grating, silicon immersion reflection and transmission gratings, high-efficiency and low-wavefront-error large echelle gratings, nanoscale metasurface gratings for spectrapolarimetry, and plasmonic infrared bandpass filters.

MISE Gratings. MDL recently fabricated and delivered concave gratings for the Mapping Imaging Spectrometer for Europa (MISE). The MISE grating design was our most challenging fabrication to date, due to the diameter and curvature (f/1.4) and wavelength range (0.8 to 5.0 µm). We had to develop new grayscale e-beam grayscale exposure schemes and concave grating fabrication methods to achieve the tightly specified spectral efficiency curve with very low scattered light.

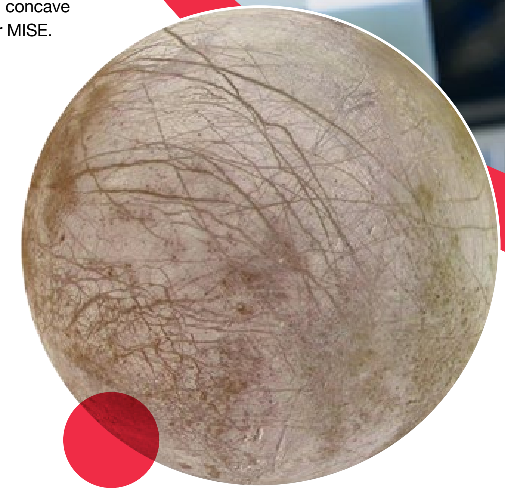
E-beam fabricated ultraviolet grating for Mars 2020 SHERLOC.







MDL e-beam fabricated concave grating for MISE.



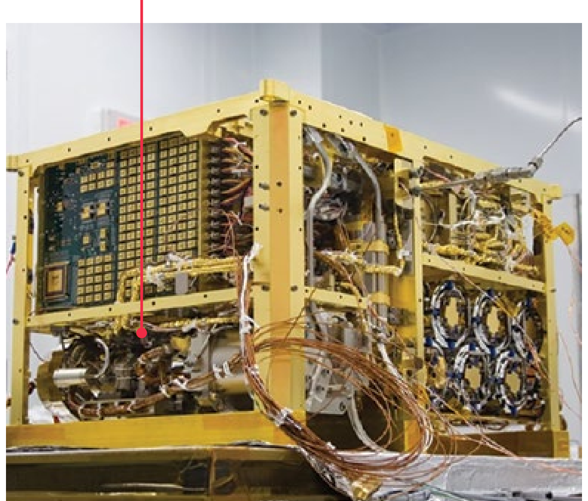
MISE will produce maps of key compounds to answer questions about Europa's ocean and its habitability.

Semiconductor lasers & integrated photonics

MDL's pioneering work on development and space qualification of unique semiconductor lasers enabled a new era in planetary and Earth atmospheric studies, but it is now in flux, transitioning to the next transformational approach to produce revolutionary new systems.

Tunable Laser Spectrometer on NASA's Curiosity Mars Rover.

Sample analysis at Mars Instrument suite.

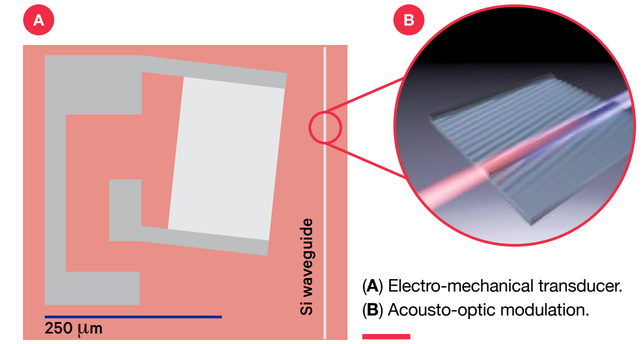


MDL developed a specialized laser that Harvard flew on a NASA high-altitude research balloon. This was part of the NASA Undergraduate Student Instrument Project (USIP) program.

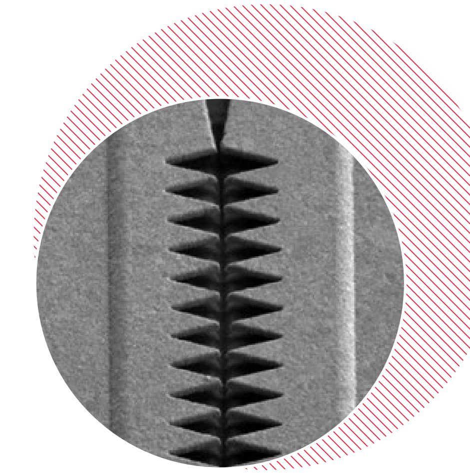
When MDL was established 30 years ago, one of its first research areas was development of semiconductor lasers. Led by the pioneering work of Dr. Siamak Forouhar, MDL created and grew the capability to produce lasers that enabled a wide variety of flight projects. The lasers were used for spectrometers that allowed precise, sensitive analyses of gas abundance and isotope ratios on Earth and for in situ planetary instruments. Generally, lasers in the relevant wavelength were not commercially available and had to meet very stringent specifications: they had to operate with high spectral purity and tunability, have high output power, and operate at ambient temperature. MDL created lasers with very long lifespans; for planetary use, their duration of use may be extensive to allow for time to reach the destination, undertake the laser's nominal operation, and, in many cases, continue during an extended mission. Thus, for many years, MDL was one of the few places that could make and qualify semiconductor lasers for space.

MDL's achievements in producing lasers for NASA missions include the first space-qualified 2.0 µm semiconductor laser for the 1998 Mars Polar Lander, an interband cascade laser at 3.27 µm for TLS (see page 18), and record high-power single-frequency lasers at 2.6 µm for the Earth Venture Suborbital (EVS-3) mission, Dynamics and Chemistry of the Summer Stratosphere (DCOTSS).

MDL now envisions evolving its traditional strength in laser development by combining it with others to jointly produce new systems as revolutionary as their predecessors. Integrated photonics, a key enabling technology in many scientific areas, is aligned with the technical competency of MDL's microfabrication tools and the laser team. Future possibilities include integrated systems for quantum photonics and the use of new materials beyond silicon for wavelength ranges in the UV and IR.



(A) Electro-mechanical transducer.
(B) Acousto-optic modulation.



Junction of field-assisted photodetector. The integrated waveguide runs vertically underneath the emitter and collector terminals, shown here with a multi-tip configuration. The gap between tips is 25 nm, and emitted electrons transit in < 20 fs.

Microwave Photonics. Photonics enables new capabilities for creating and manipulating microwave signals, with dramatic improvements in performance, flexibility, and bandwidth over existing all-electronic systems. So-called "microwave-photonic" technologies will be crucial to addressing challenges ranging from increased spectral utilization to developing state-of-the-art subsystems for future spaceborne radars. MDL is developing microwave photonics devices to address these applications. One example is the demonstration of the first integrated acousto-optic modulators in a silicon photonic circuit. These components enable direct information transduction between microwaves, hypersound, and light, permitting a variety of operations, including optical waveform synthesis, nonreciprocal light routing, and demodulation—critical functions within a future chip-scale LiDAR transceiver. Other areas of active research include ultralow-noise photonics-based microwave generation for coherent spaceborne radars and high-performance optomechanical oscillator technologies.

Integrated Photonics with Applications in Metrology. Optical metrology systems require extremely stable, narrow-linewidth, compact laser sources. Laser diodes can be made quite small with a narrow linewidth, but their stability depends upon environmental factors such as temperature and air pressure. Consequently, these small lasers require large feedback control systems to maintain particular ambient conditions.

The alternative solution developed at MDL is to feed a small fraction of the laser's output signal through a chip-scale 2x2 heterodyne interferometer, where a meter-long delay line in one branch of the interferometer creates an ultra-sensitive phase imbalance between the two optical outputs. This passive chip can measure instantaneous laser frequency variations on the order of 1 MHz, or 10 parts in 1 billion. If necessary, the sensitivity of the 2x2 heterodyne interferometer can be further improved by increasing the length of the on-chip delay line.

Top view of 0.25 m spiral waveguide.

THZ Detectors. The generation of radiation above 100 GHz is a limiting technology for a number of applications in spectroscopy and microwave photonics. Existing technologies generate photocarriers in a semiconductor via illumination with ultra-short optical pulses and then collect the photocarriers in nearby terminals. The finite speed of carriers in the semiconductor and poor overlap between the optical mode and the absorber result in poor responsivity at > 100 GHz. MDL is pursuing a potentially revolutionary technology: a field-assisted photoemitting detector. This detector uses integrated photonics to efficiently focus light into an absorbing metal. Excited electrons generated in the metal tunnel into a vacuum, assisted by a large electric field applied to the surface. The tunneled electrons travel ballistically to a nearby collecting terminal. Vacuum transport and low capacitance result in theoretical bandwidths of > 500 GHz. Improved responsivity will allow operation with continuous-wave, efficient telecommunications lasers, dramatically improving SWAP-C performance. This device would enable a host of remote sensing applications, including micro-radar and THz spectroscopy on remote platforms.

Integrated Photonics Platform for UV. The UV region is particularly attractive for applications in spectroscopy and precision metrology. It also holds great promise for planetary exploration, especially in the quest for habitable planets. For instance, instruments incorporating deep-UV light sources can facilitate the search for biosignatures and assist with bacterial identification on planetary bodies.

Currently, few optical materials are capable of operating at such short wavelengths. Furthermore, optical components for on-chip integration necessitate patterning on a scale that is highly demanding for conventional lithographic techniques.

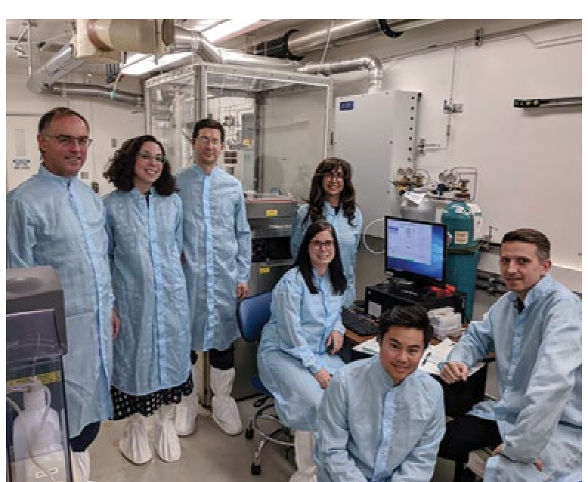
MDL is working towards realizing a chip-scale platform that exhibits low optical losses and offers nonlinear operation. Our approach relies on state-of-the-art material processing and fabrication techniques. Such a platform will enable a wide range of functionalities, from optical modulation to frequency synthesis. The developed devices will be characterized using a unique MDL measurement testbed designed, implemented, and tailored for integrated photonic devices operating in the short-visible to deep-UV range.

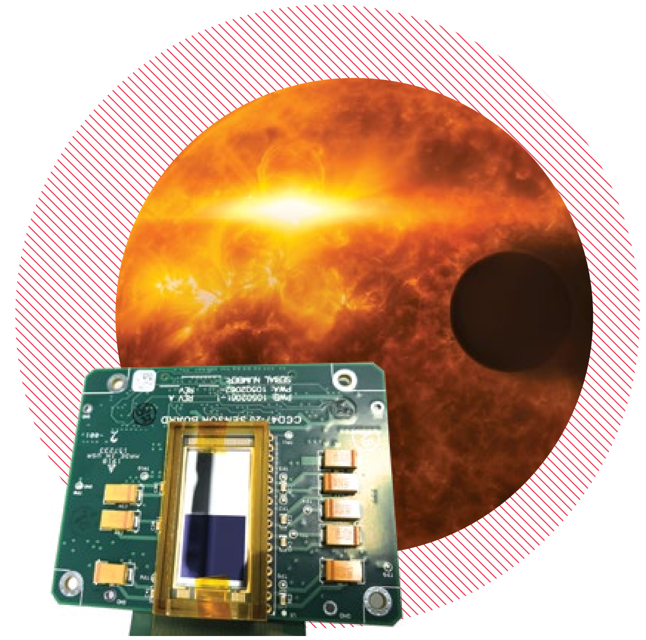
CORE COMPETENCY

UV detectors & systems

Advances generated at MDL will extend our vision to unprecedented sensitivities, enabling future discoveries and capabilities.

Nearly 30 years ago, as part of a group of early MDL recruits, a new PhD from Caltech's Physics Department started as a postdoctoral fellow at MDL and began what has become a key vehicle to explore the ultraviolet universe. Another Caltech graduate then joined, nucleating the team, and the journey of the Advanced Detectors, Systems, and Nanoscience Group began. The effort started as the first demonstration of molecular beam epitaxy (MBE) growth on charge-coupled devices (CCDs) to create high-efficiency ultraviolet detectors with stable responses and to solve the hysteresis problem that had plagued the Hubble Space Telescope's wide-field planetary camera-1. This was enabled by innovative MBE processes and concepts developed by MDL scientists Drs. Paula and Frank Grunthaner. From those beginnings emerged an internationally recognized team of experts who are leading innovations in ultraviolet instrument technologies and instruments, including high-performance detectors, highly reflective mirror coatings, filters, ultraviolet scientific cameras, and ultraviolet imaging spectrometers. The team comprises leaders in their fields who have received recognitions including, collectively, three Lew Allen Awards of Excellence; a Charles Elachi Early Career Achievement Award; three SPIE Rising Researcher Awards; a NASA Exceptional Achievement Medal; IEEE Distinguished Lecturer Award; and multiple individuals with fellow status with two in SPIE, two in the American Physical Society (APS), one in IEEE and one in the National Academy of Inventors.



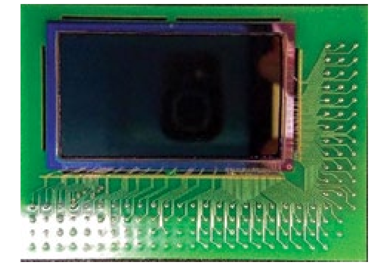


Sensor board and detector for the near UV channel of the SPARCam for SPARCS. The NUV flight candidate detectors centered at 280 nm meet baseline requirements in preliminary tests.

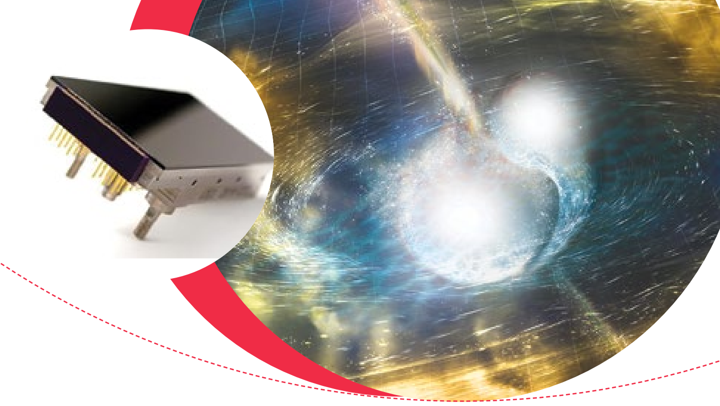
Helix Of Nebula Venus crosses the line of sight between the sun and Earth four times every 243 years in pairs separated by eight years.

The team's core efforts are to develop high-performance ultraviolet detectors via nanoengineering of surfaces and to innovate methods for band structure engineering in silicon and other material systems. The atomically precise control of surfaces and interfaces using MBE 2D doping techniques, including delta doping and, more recently, superlattice doping, ensures detection of every photon absorbed into the silicon detector, thereby rendering silicon detectors with 100% internal quantum efficiency (QE) or reflection-limited response. Furthermore, the innovative detector-integrated filters—in part enabled by atomic layer deposition (ALD)— tailor the absorption of the photons and therefore the spectral response of the detector. Because silicon is universally used for visible imaging, great investments have been made in development and advancement of detector design in silicon, all of which make silicon an attractive option as an ultraviolet imager. However, silicon is blind in ultraviolet and highly sensitive in the visible spectrum. Using MBE's 2D doping processes silicon detector surfaces are engineered to allow detection of ultraviolet photons with long-term stability and without hysteresis. The detector's response can be enhanced with dielectric coatings bytaking advantage of ALD's exquisite control and precision. The detector response can also be tailored using metal-dielectric filters (MDFs) incorporated into the detector surface. Using MDL's two ALD machines, QE records have been set in the 100-300-nm range and beyond. In this breakthrough development, high efficiency in UV is paired with an out-of-band photon rejection ratio of 3-4 orders of magnitude.

The group has expanded MDL's UV core competencies further via innovations in mirror coatings, gratings, and filters. An early version of the coatings was incorporated into the SHERLOC instrument on Mars2020 and one version was flown in the SISTINE rocket (see page 28). Similar interface engineering techniques in collaboration with SUNY-Poly have enabled air-stable GaN photocathodes—a significant improvement over the state of the art.



4kx2k SRI CMOS array (photograph courtesy of SRI) were SL doped and UV optimized.



Artist's conception of a binary neutral star merger creating gravitational waves and their electromagnetic counterpart. Dorado will detect the UV counterpart of gravitational waves. (Inset) A 2D-doped version of this device with MDF would fly on Dorado.

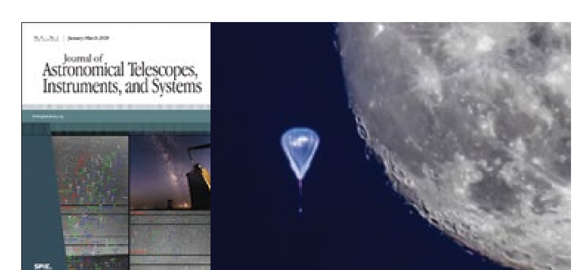
The team enjoys collaborations with universities and industry partners. Innovation often begins with identifying technology gaps through conversations with astrophysicists, planetary scientists, and other scientists, fueling needed technological innovations and paving the way for technology infusion through collaborations. To create better imaging and detection technologies, the group has formed strategic industry partnerships with groups such as Teledyne-e2v, SRI International, and STA.

MDL continues pushing performance boundaries in the UV by exploring novel device architectures, plasmonics, and metamaterials, in collaborations with academia, e.g. with the University of Pennsylvania, USC, and Dartmouth.

Enabling Astrophysics in CubeSats and Flagship Missions. MDL UV detector technologies are enabling astrophysics science in compact instruments. Two examples are: the Star-Planet Activity Research CubeSat (SPARCS)—a 6U CubeSat mission led by Arizona State University (PI, Evgenya Shkolnik) and Dorado—A Small Explorer-Mission of Opportunity selected for step 1 and led by Goddard Space Flight Center (PI, Brad Cenko), comprising two UV instruments in two 12U cubesats. Both missions rely on the breakthrough MDL development that tailors the UV response of the detector by incorporating visible rejection filters into the detector. The detectors in both of these missions are the result a collaborative effort with Teledyne-e2v to apply MDL innovations to their CCDs.

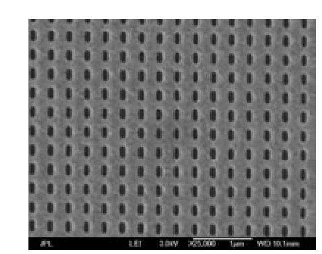
2D-doped detectors and MDFs pioneered by this MDL group have enabled several other astrophysics and planetary concepts. Two of four flagship mission concepts in astrophysics have baselined their detector or coating innovations from this group.

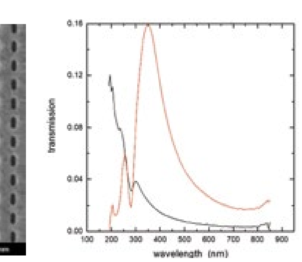
The results of the FIREBall flight were analyzed and published in JATIS and made the cover of its special issue on detectors.



FIREBall-2 Flight of High-Efficiency UV Detector Enables Detection of Bright Targets. Analysis of flight data from the Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall or FB)-2 revealed detection of targets not observed with FIREBall-1. When FB-2 was launched in the Fall of 2018, the instrument performed beautifully despite the shortened flight due to a balloon defect. These results were analyzed and described in the paper, "Delta-doped electron-multiplying CCDs for FIREBall-2," by lead author Gillian Kyne, who led the delivery of the FB-2 detector system. The paper was featured on the cover of the Journal of Astronomical Telescopes, Instruments, and Systems (JATIS)-Detector special issue in January 2020. The detection of GALEX targets by FB-2 is in large part because of the use of MDL's delta-doped and custom-coated Teledyne-e2v's electron multiplying CCD (QE >5x over FB-1 detector).

Exploring Metamaterials for Tailoring Response. Using asymmetric response for polarization discrimination in transmissive filter structures at UV wavelengths while rejecting of out-of-band wavelengths were rectangular features. More optimization will be done to further reduce overlap between the two contributions. SEM image of a rectangular hole array in Al. The large aspect ratio of the rectangles (50 x 150 nm) produces a large splitting in the transmission peak of the two polarizations (right).





Highly Uniform, High-efficiency Superlattice-doped CMOS Arrays for Planetary and Astrophysics Applications. In collaboration with SRI International and the Applied Physics Laboratory, MDL received and processed wafers with the same design as the Europa-Clipper EIS—Europa Imaging System. These SRI CMOS devices are superlattice doped, optimized for FUV and NUV, and baselined for an explorer mission.

Mid-infrared detectors

The goal of the Infrared Photonics technology at MDL is to develop novel high-performance III-V compound semiconductor-based infrared detectors and focal plane arrays for NASA and other government agencies, thereby enhancing U.S. competitiveness worldwide.

Dr. Gunapala is preparing to open the front flange of an Integrated Dewar Cooler Assembly (IDCA) to install a focal plane array on the cold finger of the IDCA.

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

IR DETECTORS

This year, MDL is celebrating its 30th anniversary as the leading semiconductor device fabrication facility in the NASA community. Making infrared detectors has long been an MDL core competency, one that has been enabled by having full access to MDL's unique, constantly evolving, and constantly improving semiconductor fabrication facility. This irreplaceable facility was essential during the development of breakthrough infrared detector technologies such as High-Operating-Temperature Barrier Infrared Detectors (HOT BIRDs) and delivery of infrared focal plane arrays to flight projects such as the CubeSat Infrared Atmospheric Sounder (CIRAS) and the Hyperspectral Thermal Imager (HyTI).

Those working on this technology are eminent in their field and have been recognized with many awards and commendations. Some selected recognitions include a NASA Outstanding Leadership Medal, two NASA Exceptional Engineering Achievement Medals, a NASA Early Career Public Achievement Medal, an IEEE Aron Kressel Award, two IEEE Distinguished Lecture Awards, an MSS Herschel Award, a SPIE George Goddard Award, and two feature articles in Applied Physics Letters. They have produced over 350 publications and hold 26 US and international patents on infrared detection technologies. Many of the infrared detector technologies developed at MDL, including the HOT BIRD, have been successfully transferred to US industries for government and commercial applications. FLIR, one of the leading infrared camera manufacturers for the commercial market, has also licensed these patents.

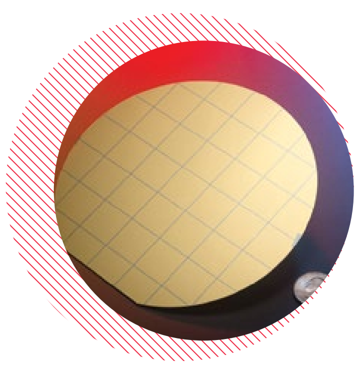
At the heart of this area of work is the integrated design, fabrication and delivery of novel infrared (short-wave, mid-wave, long-wave, and very-long-wave) focal plane arrays based on III-V compound semiconductors. The Infrared Photonics Technology Group in the MDL family effectively owns this competency and has a goal of developing new high-performance infrared detectors and focal plane arrays for NASA and other government agencies, thereby enhancing the United States' competitiveness worldwide.

This group has been at the forefront of advanced infrared detector technology development and has developed many patented concepts. Capabilities include novel detector design, epitaxial material growth, end-to-end large-area detector fabrication process, characterization of infrared focal plane arrays, and delivery of focal planes and integrated dewar cooler assemblies to infrared instruments.

One of the group's outstanding recent achievements has been the development of the antimonides type-II superlattice-based HOT BIRDs for space and terrestrial applications. HOT BIRD is a breakthrough infrared detector technology capable of operating at 150K with spectral coverage of not only the entire mid-wavelength infrared (MWIR) atmospheric transmission window (3–5 mm) but also the short-wave infrared (SWIR, 1.4–3 mm) and the near infrared (NIR, 0.75–1.4 mm) transmission windows with very high quantum efficiency. The HOT BIRD focal plane array is at the heart of CIRAS and HyTI, the 6U CubeSat that was recently selected by NASA's In-Space Validation of Earth Science Technologies (InVEST) program.

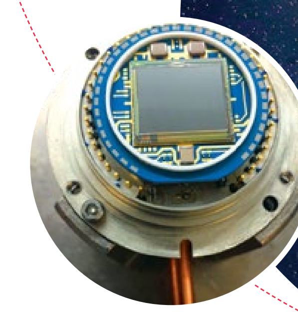
Innovations at MDL enable observations of our planet in an infrared region just beyond our reach, as well as mapping of the world's ecosystems, defense, cloud structures, and natural disasters. However, the current state of the art is never sufficient, even in a technology area that has produced devices that work at previously unimaginably high temperatures. The ultimate goal is to develop infrared sensor assemblies that could operate in space solely on passive cooling.

Products for custom applications and space exploration are designed, fabricated, characterized and delivered and include mid-wavelength and long-wavelength infrared instruments and integrated sensor assemblies. Other products include large-format, state-of-the-art HOT-MWIR and LWIR BIRD focal planes and high-performance multi-band and broadband infrared imaging solutions. These new technologies, designs, system integration, and instrumentation can enable new sensing capabilities that were previously not possible. There is also a quest for monolithic integration of metasurfaces such as flat lenses, filters, and polarizers to further increase the sensitivity and operating temperature of infrared detectors.

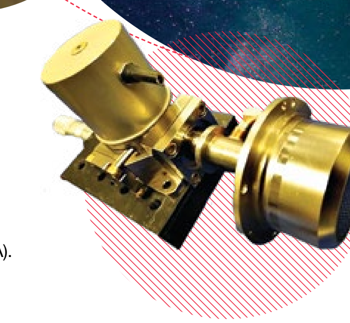


Twenty-five 2Kx2K HOT BIRD detector arrays on a 6-inch GaSb wafer.

Illustration depicting the HyTI CubeSat in low Earth orbit.



FPA mounted on cold finger before IDCA integration process.



An Integrated Dewar Cooler Assembly (IDCA).

Artist rendering of CubeSat Infrared Atmospheric Sounder (CIRAS) based on MWIR HOT-BIRD focal plane array.

Two megapixel and one VGA, 1Kx1K focal planes 20 and 30 microns pixel pitch.

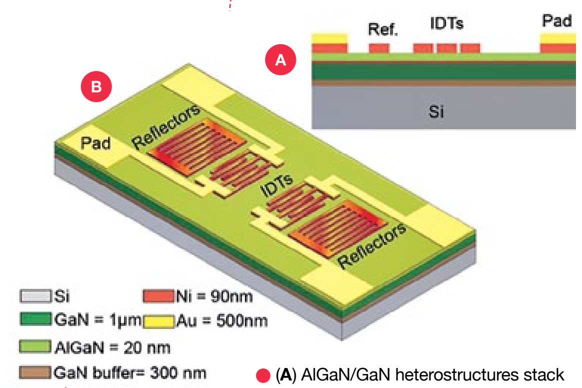
MEMS & microsystems

MEMS technology continues to shrink the mass, size and power requirements of vital instruments and systems needed for space missions, thus also shrinking the mission cost.

The history of MEMS activities at MDL is as old as MDL itself. In the late 1980s, the advent of silicon micromachining led to the development of devices such as accelerometers, magnetometers, and thermal infrared detectors. In the past few years, MEMS technology has been used to micro-fabricate the Pre-Concentrator (PC) and Gas Chromatograph (GC) unit (together forming the PCGC subassembly) of the SAM instrument, which checks the quality of the cabin atmosphere on the International Space Station (see page 68). The unit was designed, fabricated, and tested at MDL and uses a novel MEMS technology to produce the unit, which has 75% less mass and 85% less volume than its predecessor.

MEMS technology has considerable breadth, but recently, MDL work in this area has focused on three development efforts: Gallium Nitride Clocks (GaNTiming), a Resonant IR Detector for operation in High Temperature Environments (HotIR), and a Tunable Pitch Diffraction Grating using Surface Acoustic Waves (Tunable SAW Grating). The aim in all cases is to produce performance equivalent to that of state-of-the-art devices or components but with reduced mass, size and power requirements. This is a particularly valuable contribution to CubeSat missions, many more of which can now be launched because of the lower overall cost.

Making MEMS components and devices requires most of MDL's available technologies, including electron-beam lithography, silicon micro-machining, aluminum nitride sputtering, and electron-beam deposition. However, it is the skillful design and integration of these approaches that marks the successful implementation of MEMS technology. This MDL technology has a history of past and present successes and achievements. We can extrapolate these successes to the future, confident in the ability to fulfill the ambition of continuing to reduce the size and improve the performance of the products developed with MEMS technology.



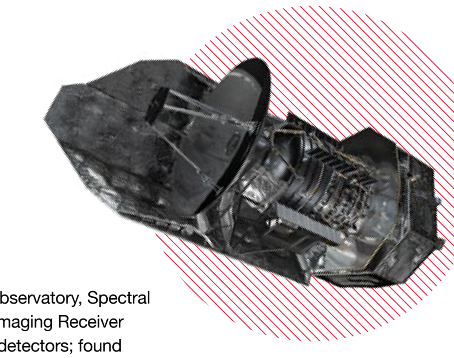
(A) AlGaN/GaN heterostructures stack with 2DEG and with fabricated IDTs/pads for SAW devices, **(B)** 3D diagram of the fabricated SAW.

Tunable SAW-Based Diffraction Gratings. Grating-based imaging spectrometers are some of the most common remote sensing instruments in planetary, Earth, and astrophysical sciences. In such instruments, the grating pitch affects the spectral resolving power, spectral coverage versus overlap, image quality, and payload size, among others. In all instruments in current/planned missions, the diffraction grating is machined such that once it is patterned, its pitch cannot be changed. Therefore, to cover a wide spectral range, a number of diffraction gratings are needed, resulting in increased payload size and cost. The JPL Research and Technology Development program sponsored a project to develop a tunable diffraction grating using surface acoustic waves (SAW) to enable broadband spectrometers with high resolving power, without trading off spatial resolution. The final tunable pitch diffraction grating will lead to a new class of spectrometers that have high spectral resolution (<0.5 nm at 1 μm wavelength) over a large wavelength range (>2 octaves). Such instruments will enable improved science at planetary bodies by permitting identification of more surface materials.

The delay line between two sets of interdigitated transducers (IDTs) supports the SAW with surface topography that is naturally sinusoidal. In our approach, this delay line is used as the diffraction grating without actually patterning anything on the delay line itself (Fig. A). As the SAW is sinusoidal, it can only support m = -1, 0, +1 diffractive orders. By working near the Littrow angle, a mechanical baffle and beam dump can be placed to eliminate the spectral overlap. To tune the frequency and thus the pitch of the diffraction grating, we tune the pitch of the IDTs using phased array. More specifically, the λSAW is varied by introducing a matching phase delay to the IDT, similar to the constructive interference of a phase array radar (Fig. B).

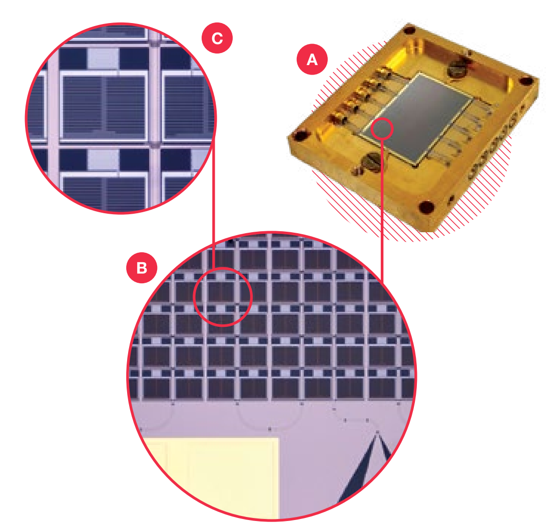
To prove the concept, the frequency of the device was demonstrated to be tunable by changing the configuration of the IDT. A tunable device was fabricated on a lithium niobate substrate. For this demonstration, the IDT finger width was 5.5 mm. The frequency could be tuned by tuning the effective spacing of the IDTs by applying specific phases to each IDT finger. The prototype SAW grating covers a frequency range of 86 MHz to 360 MHz, corresponding to an optical range of 1.3 μm to 9 μm.

Super-conducting devices



Herschel Space Observatory, Spectral and Photometric Imaging Receiver (SPIRE): enabling detectors; found distant infrared-luminous galaxies.

MDL's superconductor technology will power communication in the next generation of crewed missions and enable the precise measurement of the smallest things, from single photons to tiny shifts in temperature, to answer the biggest questions about our universe.



(A) A 10,000 MKID PtSi on Sapphire array for DARKNESS mounted in its microwave package.

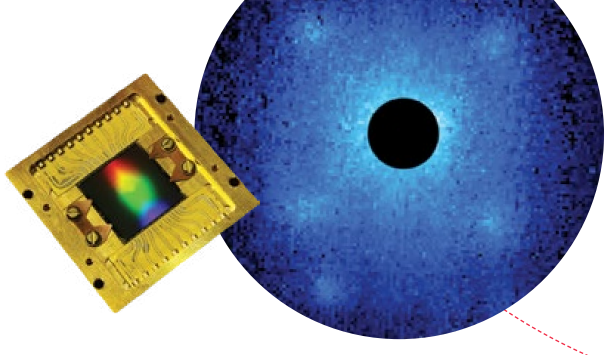
(B) Detail image of the array showing the CPW transmission line with bond pad for one feedline.

(C) Further detail of several MKID pixels. The densely meandered patches at the top of each pixel are the photosensitive inductors, and the large sparse sections are the interdigitated capacitors used to tune each MKID to a unique resonant frequency.

Superconductors operate at low temperatures with a small energy gap and highly nonlinear electrical properties, making them uniquely suited for use in ultrasensitive electromagnetic detectors. Even before MDL's founding 30 years ago, the JPL Superconducting Materials and Devices Group was exploiting these characteristics to develop and deploy novel superconducting sensors and closely related non-superconducting sensors for applications in astrophysics; Earth, planetary, and cometary sciences; and optical communications.

Heterodyne Mixers. The highly nonlinear current-voltage characteristics of superconducting tunnel junctions enable heterodyne mixers with unsurpassed sensitivity from millimeter (mm)-wave to terahertz (THz) frequencies. Beginning in the mid-1980s, Dr. Rick Leduc and several JPL coworkers, in collaboration with Caltech, produced tunnel-junction-based mixers for deployment in terrestrial telescopes, balloons, aircraft, and the Herschel Space Observatory, which operated from 2009–2013 . In 2019, worldwide excitement over the first images of a black hole led to interest in new mixers for the Next Generation Event Horizon Telescope and even Very Long Baseline Interferometry (VLBI) in space; these technologies would deploy in three to five years and in the next decade, respectively. Additionally, Dr. Daniel Cunnane is leading development of Josephson and Hot Electron Bolometer (HEB) mixers based on high-temperature superconductors for use at temperatures up to 20 K and frequencies above 1 THz.

Transition Edge Sensors. In the transition between a normal metal conductor and a superconductor, very small changes in temperature cause large changes in resistance. For two decades, Anthony Turner and coworkers at MDL have collaborated with Caltech and other institutions to produce imaging arrays based on Transition Edge Sensor (TES) bolometers. Increasingly complex mm-wave focal plane arrays (FPAs) have been deployed at the South Pole on several generations of radio telescopes, including the Background Imaging of Cosmic Extragalactic Polarization (BICEP) telescopes (i.e. BICEP-2, BICEP-3, and the BICEP Array), and the Keck Array. These instruments have enabled cosmic microwave background (CMB) polarization measurements with unprecedented sensitivity to search for the imprint of gravity waves on the CMB as a signature of inflation in the earliest moments of the universe. Such technical demonstrations and scientific studies are critical to making the case for CMB satellite observatories such as PICO, CoRE, and LiteBIRD, which are currently proposed or under study for startup in the coming decades.

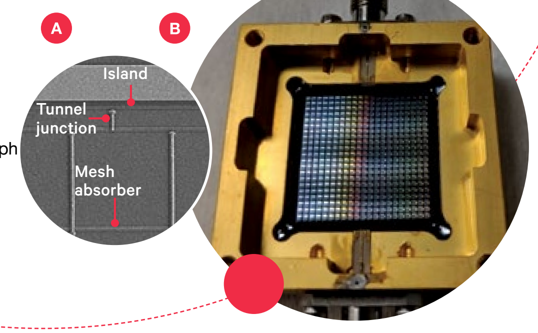


MEC array. Mounted chip assembly of 20k pixel MEC array: 140 X 146 pixels with 10 microwave drive lines, 150 um pitch, 22 X 22 mm.

On-sky diffraction limited Y-band image from MEC of quintuple star system Theta Ori B.

Kinetic Inductance Devices. Superconductors have a kinetic inductance that is sensitive to changes in temperature and Cooper pair density (effectively the number of weakly bound electron pairs that cause superconductivity). In a Kinetic Inductance Detector (KID), absorption of photons results in a shift in the resonance of an LC circuit (an inductor/capacitor tuned resonant circuit). In a KID array, each pixel has a unique resonant frequency and a single reactively coupled microwave feedline can read out thousands of pixels. Microwave KIDs (MKIDs) originated two decades ago with Drs. Peter Day and Rick Leduc at JPL, Dr. Jonas Zmuidzinas at Caltech, and other coworkers. The high sensitivity of MKIDs and ease of multiplexing led to wide interest in MKIDs for imaging arrays over frequencies from mm-wave to UV for terrestrial, planetary, and astrophysical investigations. A recent example of this technology in action is a passive mm-wave telescope for use where optical wavelengths are obscured; the telescope is being developed with Office of Naval Research (ONR) support (see page 15). This instrument also serves as a technology demonstrator for new astrophysics experiments in the coming decade, such as the Stage-4 CMB experiment. At shorter wavelengths, far through mid-infrared (IR), MKID arrays are under development for the Terahertz Intensity Mapper (TIM) balloon experiment and flight mission concepts Galaxy Evolution Probe (GEP) and the Origins Space Telescope (OST). In the visible/NIR region, MKIDs can sense individual photons and measure their energies, allowing for integral field spectroscopy. Working in this regime, Dr. Bruce Bumble is part of an ongoing collaboration with Dr. Ben Mazin's group at the University of California Santa Barbara to develop the MKID Exoplanet Camera (MEC).

A suite of other promising technologies grew out of the initial MKID development. For example, thermal KIDs (TKIDs) are bolometers that use the temperature-sensitive kinetic inductance of a superconducting film in a resonator to monitor temperature shifts from changes in loading. TKIDs also offer multiplexing that is extendible to large arrays. Currently, Dr. Roger O'Brient is leading the development of a 250 gigahertz (GHz) camera with 20,000 such detectors for a BICEP deployment in 2021. Additionally, a microwave frequency version of the kinetic inductance traveling-wave parametric amplifier developed at MDL has demonstrated quantum limited sensitivity over nearly an octave of bandwidth. Finally, Dr. Peter Day, Dr. Rick Leduc, and Dr. Byeong Ho Eom continue to develop the Kinetic Inductance Parametric Upconverter (KPUP) for readout of TES bolometer arrays, and a highly efficient frequency multiplier is also being developed (next page).

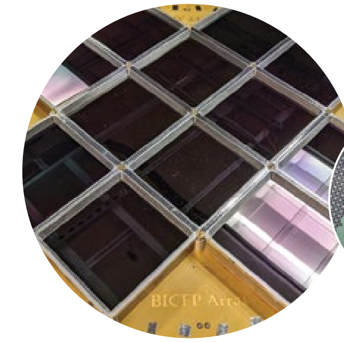


(**A**) Scanning electron micrograph of an individual detector. (**B**) QCD chip mounted in RF box.

Quantum Capacitance Detectors. Combining superconductivity with nanoscale tunnel junctions introduces new properties, leading to an artificial quantum two-level system, the single-Cooper-pair box (SCB). The quantum capacitance detector (QCD) is a far-IR sensor based on the extreme sensitivity of the SCB to pair-breaking radiation that is being developed by Drs. Pierre Echternach, Andrew Beyer and Matt Bradford. The QCD consists of an SCB embedded in a superconducting resonator. A single quasiparticle tunneling event produces a frequency shift comparable to or larger than a resonator linewidth. QCDs have demonstrated photon shot noise limited performance with useful optical efficiency for optical loadings between 10^{-20} and 10^{-18} W, corresponding to a noise-equivalent power (NEP) below 10^{-20} W/Hz$^{1/2}$. The QCD is being developed as a far-IR direct detector for the Origins Survey Spectrometer, an instrument intended for the Origins Space Telescope. The telescope is under consideration as a flagship mission in the 2030s.

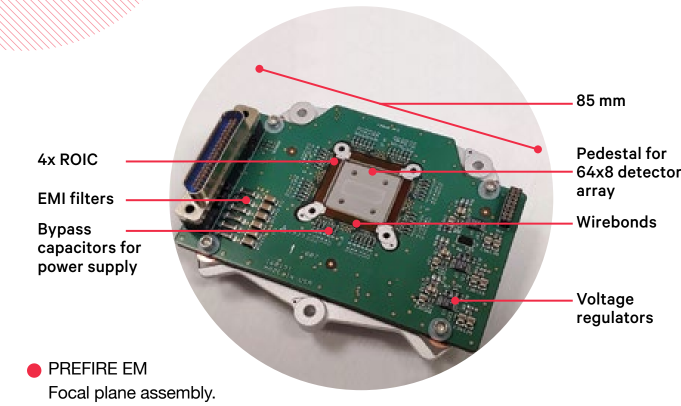
Superconducting Nanowire Single-Photon Detectors. The Superconducting Nanowire Single-photon Detector (SNSPD) is based on a narrow superconducting wire biased near its critical current. Absorption of as little energy as a single photon drives the wire into the normal state, producing a voltage pulse. SNSPDs provide the highest available timing resolution from UV to mid-IR wavelengths. Over the past decade, the MDL team led by Dr. Matt Shaw has been a leader in SNSPD development, currently holding world records for SNSPD detection efficiency, timing resolution, active area, and dark counts. MDL also collaborates extensively with other leading groups, including MIT, the MIT Lincoln Laboratory, and the National Institute of Standards and Technology (NIST) Boulder. MDL SNSPDs have a central role in the Deep Space Optical Communication (DSOC) ground terminal for the Psyche mission scheduled for launch in 2022. They are also being integrated into several new NASA laser communication demonstration projects, including Optical-to-Orion, a crewed flight project; the RF/Optical Hybrid project, in which a retrofitted Deep Space Network antenna works as an optical telescope; and SETH, a Pre-Phase A heliophysics SmallSat led by the Goddard Space Flight Center. Prospects for the coming decades include mid-IR SNSPD focal plane arrays for exoplanet transit spectroscopy on the Origins Space Telescope and ultra-low-jitter SNSPDs for an MIT Lincoln Lab-proposed flight terminal for space-to-ground quantum teleportation.

Deep Space Optical Communications (DSOC) will fly on the Psyche Mission in 2022.



Bicep Array Telescope: Focal plane for 30 and 40 GHz CMB observation.

New dual band dual polarization TES Detector Pixel (30 and 40 GHz).

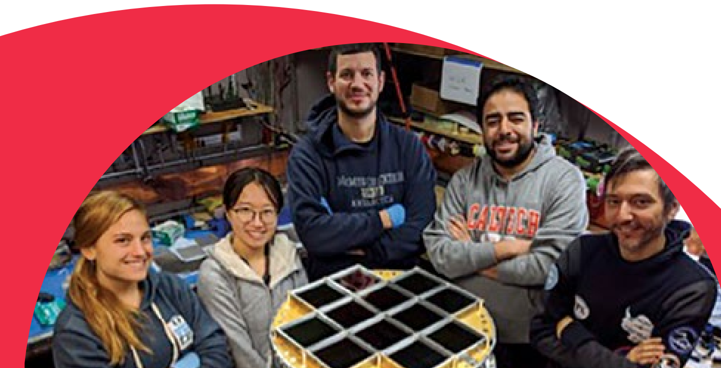


PREFIRE EM Focal plane assembly.

Higher-Temperature (non-superconducting) Detectors. Thermopiles are essentially series-connected thermocouples. Thermopile far-infrared (FIR)-IR imaging arrays are a non-superconducting technology that grew out of early MDL superconducting sensor development over 20 years ago. Frustration with materials problems in high-temperature superconductors led to the development of uncooled detectors where extreme sensitivity is not required and the desired operating temperature is too high for conventional superconductors. Development is currently being led by Dr. Matt Kenyon. Recent applications include FIR spectrometers for the Radiation Budget Instrument (RBI) and the planned Polar Radiant Energy in the Far Infrared Experiment (PREFIRE).

2019 Highlights

BICEP. In December of 2019, an MDL TES focal plane was integrated into the 30/40 GHz BICEP Array telescope at the South Pole Station. This camera will help the BICEP CMB polarimetry program monitor galactic synchrotron foregrounds as part of ongoing efforts to constrain the inflationary tensor/scalar ratio r. The focal plane contains 526 antenna-coupled TES bolometers and is the most sensitive to date for this application. JPL's collaborators, including Caltech, Harvard, Stanford, and the University of Minnesota, will field test these detectors and advance them to Technology Readiness Level 5. Drs. Roger O'Brient and Anthony Turner designed the modules and detectors in collaboration with Caltech students and staff. Dr. Clifford Frez, Krikor Megerian, and Dr. Alexis Weber fabricated the detector arrays at MDL, and Dr. Turner integrated them into their packaging with readout electronics. JPL scientist and Caltech Professor Jamie Bock has led the development of the camera itself. The BICEP Array will have a total of four cameras, with JPL providing three additional focal planes over the next four years. This work is supported by the JPL Research & Technology Development (R&TD) program and the NASA Strategic Astrophysics Technology program.



2019 Technology Developments

PREFIRE. As the PREFIRE mission approaches its 2021 launch date, an MDL team led by Drs. Matt Kenyon and Giacomo Mariani has demonstrated a new focal plane array (FPA) board that meets mission requirements; completed a new flight FPA board that is even more compact than the EM FPA board, enabling it to fit into the small payload volume; and developed a flight FPA design that minimizes the capacitance between the detector chip and ground to reduce the readout integrated circuit (ROIC) noise.

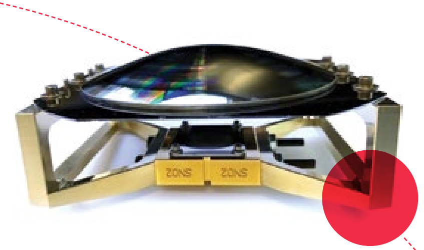
Frequency Multiplier. High-efficiency frequency multiplication was recently demonstrated using a device similar to the microwave parametric amplifier. The nonlinear kinetic inductance of a NbTiN microstrip was used to generate harmonics of a fundamental signal. A large percentage of the fundamental power can be converted to the third harmonic, creating a very highly efficient frequency multiplier. In this initial demonstration, the device achieved approximately 40% efficiency at 1 K and approximately 30% efficiency at 4 K, converting a 34 GHz signal to a 104 GHz output with 2-3% bandwidth. Simulations show that the efficiency can be improved by a factor of two. A major benefit of this technology is that most of the power that is not converted to the desired output is reflected off the chip rather than lost as heat on the cold stage. This technology could have a major impact on future heterodyne receivers to enable much larger arrays than have been achieved in the past. Each pixel of an array needs a local oscillator, and existing technology requires 0.5-5 W of power per pixel. The proposed technology should scale to 1-2 THz and require just a few milliwatts of power per pixel. This work is funded by the JPL R&TD program. The team includes Principal Investigator Dr. Daniel Cunnane and Co-Investigators Drs. Peter Day and Rick Leduc.

SNSPD. In 2019, in collaboration with NIST Boulder and Dr. Karl Berggren's group at MIT, the JPL SNSPD team demonstrated both kilopixel imaging arrays and timing resolution below 3 picoseconds (ps). In collaboration with Dr. Rajeev Ram's group at MIT, they also demonstrated the first optical readout of an SNSPD using a cryogenic modulator.

The Caltech team installs the JPL focal plane into the first BICEP Array camera at the South Pole Observatory (left to right: student Sofia Fatigoni, student Cheng Zhang, staff scientist Lorenzo Minutolo, student Ahmed Solimon, and postdoctoral researcher Dr. Alessandro Schillaci).

Submillimeter devices

Submillimeter-wave and remote-sensing technologies are used to develop components and technologies that enable spaceborne instruments based on high-resolution heterodyne spectrometers. These instruments can be used for Earth remote sensing missions, planetary missions, and astrophysics observatories.



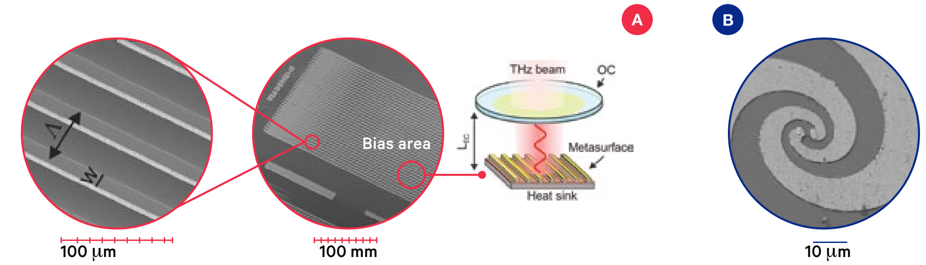
A 7-cm-diameter low-profile silicon lens antenna fabricated at MDL. The antenna has a leaky-wave feed and is less than 7 cm in height, making them very suitable for CubeSat/SmallSat platforms.

The Microwave Instrument for the Rosetta Orbiter was built at JPL.

The Submillimeter Wave Advanced Team (SWAT) Group at MDL was started in early 1990 with the ambitious goal of enabling new science missions using terahertz (THz) heterodyne instruments. At that time, most people had never heard of THz, even though at least 98% of the detectable radiation energy in the universe falls within the THz range. However, the demand for exploring the unknown 98% of THz radiation compelled MDL to start the SWAT Group as a pioneer in THz research and to transform the status quo in THz technology with breakthrough developments. As envisioned initially, MDL has successfully delivered many critical scientific instruments. For example, the Microwave Limb Sounder (MLS) instrument measures OH radicals that play a critical role in the ozone destruction cycle. Scientists using Microwave Instrument for the Rosetta Orbiter (MIRO) mapped the distribution of water in the plume of Comet 67P/Churyumov-Gerasimenko as it approached the Sun. Additionally, the Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel spacecraft enabled advances in astrophysics by measuring the dynamics of star formation.

Just as every person has unique fingerprints, atomic and molecular gases have unique spectral lines. The heterodyne THz spectrometer can identify the unique spectra of these gases in THz for use in earth science, planetary science, astrophysics, and heliophysics applications. Furthermore, the THz spectrometer can identify the adjacent spectral lines of different molecules because of its high spectral resolution (>10^6). As an example of this emerging technique, a THz Limb Sounder (TLS) can identify the 2.06 THz atomic oxygen (OI) emission line and use it to measure the wind profile at an altitude of 100 – 140 km on Earth with the help of the wind-induced Doppler shift of the 2.06 THz spectral line. It can also determine [OI] density and neutral temperature. The TLS instrument has many useful advantages: it does not require cryogenic cooling, requires low power, and is highly sensitive due to the nature of GaAs Schottky diodes, the critical mixer component used in heterodyne receivers. The MIRO instrument mentioned above used the same principle as the TLS to detect the spectral lines of water (556 GHz) in the plume of Comet 67P. MDL has been developing spectrometers at different frequencies to detect different atoms and molecules, including 1 THz spectrometers for water, 1.9 THz spectrometers for ionized carbon, 2.5 THz spectrometers for ionized nitrogen, and 4.7 THz spectrometers for neutral oxygen.

Although THz technology has made dramatic advances, the ultimate goal would be to produce a real-time, low-cost, and compact THz heterodyne imager. The SWAT group at MDL is the closest to achieving this dream because of MDL's capabilities in packaging and GaAs Schottky diodes. Current packaging uses conventional CNC metal machining, placing an upper limit on the number of pixels. By contrast, a novel packaging technique developed at MDL uses silicon micromachining and allows for a limitless increase in pixel numbers because of its batch-processing feature.



Micrographs of the subwavelength emitting metasurface of a UCLA made QC-VECSEL device (**A**) and of a JPL made MgB_2 HEB mixer device (**B**) used in the recent THz receiver demonstration. The mixer element is a small bridge seen in the center of the spiral antenna structure covering the 0.6-5 THz spectral range.

Terahertz Schottky diode based sources developed at MDL can be used to observe star forming regions with very high spectral resolution.

The greater the number of pixels, the closer the instrument gets to real-time scanning. Improvements in GaAs Schottky diodes also continuously break the world record for output power in frequency multipliers. Additionally, the early adoption of complementary metal-oxide-semiconductor (CMOS) technology for THz applications enables instruments that are both compact and low cost. Consequently, the mass, volume, and power requirements of CMOS-based radar, spectrometers, local oscillators, synthesizers, and other devices have been reduced by an order of magnitude. MDL will continue leading delivery efforts for THz instruments.

A THz heterodyne instrument comprises an antenna, mixer, local oscillator, intermediate-frequency (IF) amplifier, back-end spectrometer, and CNC-machined waveguide blocks. Each component plays a critical role in the successful implementation of future THz heterodyne instruments. THz heterodyne instruments are a core competency because of MDL's capability to design and fabricate all these core components. Major progress has been made in developing most of the components, but in the last year, the greatest progress was made in antenna and mixer technologies, as described below.

Low-Profile Lens-Based Ultra-Light High-Performance Antenna at Submillimeter Wavelengths. Work at MDL has led to the development and fabrication of the first low-profile high-gain THz antenna for CubeSat or SmallSat platforms. The antenna is based on a leaky-wave feed that illuminates a collimating silicon lens. The prototype 7-cm-diameter low-profile antenna is directly integrated on the spacecraft and does not require an external feed (as is needed for reflecting arrays) or a deploying mechanism. The thickness of the lens-based antenna is 7.2 cm, allowing the entire instrument, along with the antenna, to fit in a small volume.

For the low-profile antenna, a plane-convex lens was made with high-resistivity silicon with a 0.25 f-number, thus reducing the overall thickness of the antenna. An antireflection coating of Parylene was deposited on both faces of the lens to minimize silicon-air reflection losses. By using a high-resistivity silicon wafer (> 10 kΩcm), the dielectric losses are negligible in the 500-600 GHz band. The structure was fabricated using Deep Reactive Ion Etching (DRIE) of high-resistivity silicon wafers to etch 15 µm -radius holes on a hexagonal lattice with a 25-µm radius.

This breakthrough was achieved by Dr. Goutham Chattopadhyay and his team.

THz MgB_2 HEB Receiver with Novel Solid-State Local Oscillator Sources. An MDL team has demonstrated the operation of a THz heterodyne receiver based on the MgB_2 hot-electron bolometer (HEB) mixer with novel high-power solid-state local oscillator (LO) sources. MgB_2 is a high-temperature (≈ 39 K) superconductor that is a very attractive material for making HEB mixers because of the high operating temperature (~ 20 K) and the large intermediate (IF) bandwidth of ~ 7 GHz that it provides. MgB_2 HEB mixers integrated with compact solid-state LO sources can be prototyped for real astrophysics balloon and SmallSat instruments.

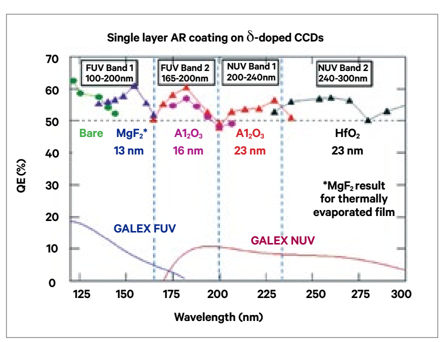
Recently, the same team gained access to the novel THz Quantum Cascade Vertical External-Cavity Surface-Emitting Laser (QC-VECSEL) developed at UCLA. Compared to the previous QCL, the new device is more powerful (up to 10 mW), operates at higher temperatures (at least 77 K) and has a very good quality Gaussian beam, which is important for telescope applications. QC-VECSEL LOs open the door to the development of new advanced heterodyne array receivers at frequencies beyond 2 THz, which have been difficult to access before. Many activities are starting, and the goals are to achieve QC-VESCEL devices at MDL and adjust the power consumption and dissipation of the lasers to make them compatible with balloon and satellite platforms.

Another more-conventional THz LO technology has been advanced by the recent development of a high-power (~ 100 µW) 1.3-1.5 THz Schottky-diode-based frequency multiplier source. This source is sufficient for pumping an MgB_2 HEB mixer. The importance of this demonstration is in enabling THz heterodyne receivers for applications on SmallSat vehicles, where 20 K cryocoolers required for MgB_2 HEB operations are affordable. A concept for such a receiver, called the Galactic Ecosystems Mapping SmallSat (GEMS), is now under consideration by NASA. A reduction in the mixer device size (currently underway) will reduce the LO power requirement by another factor of ~ 20, thus opening the door to the development of array receivers for SmallSats.

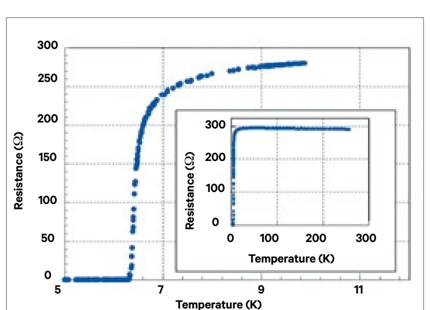
These developments were achieved by Dr. BorisKarasik and his team. The QC-VECSEL LO was used in collaboration with Professor B. Williams and Dr. C. Curwen (UCLA). Dr. Jose Siles developed the high-power frequency multiplier source. The GEMS concept was originated by Dr. Jorge Pineda.

Next-generation fabrication technologies

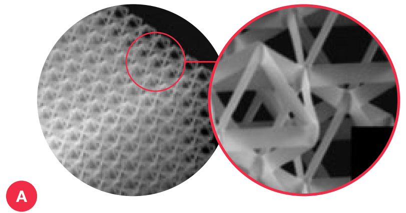
MDL's capabilities in atomic-scale processing are enabling breakthroughs in the fabrication of semiconductors, superconducting films, detectors, and optoelectronic devices. Some of these devices are only nanometers thick, and some have set world records.



C ALD Coatings for silicon CCDs.



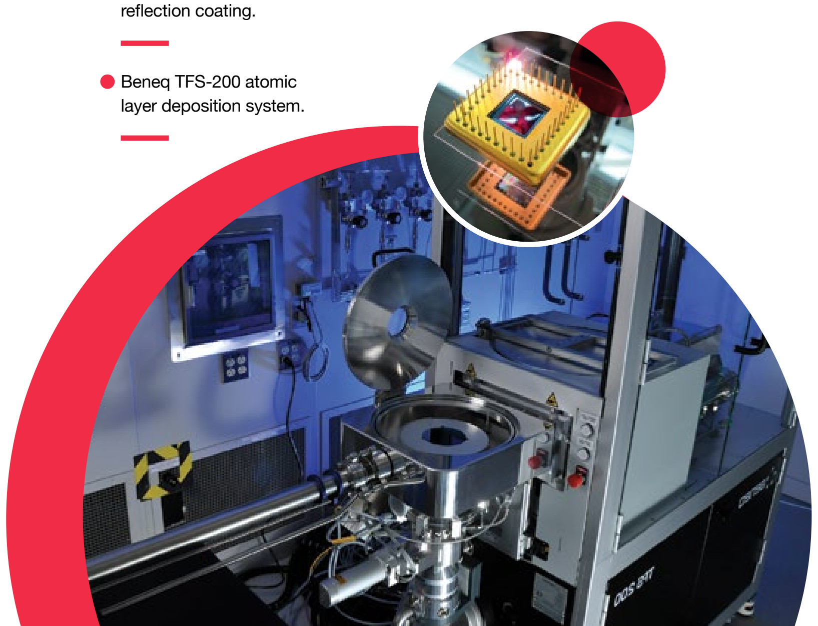
D Superconducting ALD films.



A 3D nanostructure coated by atomic layer deposition.

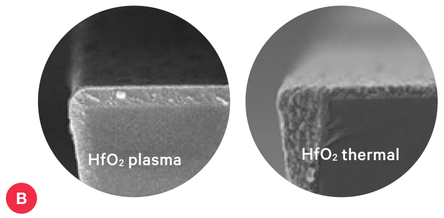
To clearly differentiate itself based on the quality and performance of the products it delivers, MDL has consistently focused on developing techniques and processes that allow for exquisite control at the atomic scale. As far back as 1989, MDL used techniques such as e-beam lithography and Molecular Beam Epitaxy (MBE) to achieve atomic-scale precision in patterning and materials growth. With the advent of Atomic Layer Deposition (ALD) and Atomic Layer Etching (ALE), new capabilities have been achieved, leading to a host of new MDL microdevices created using atomic-scale processing.

Atomic-Scale Processing: ALD Applications from Coatings and Films to Detectors. ALD deposits thin films with unequaled conformality, uniformity, and angstrom (Å) -level thickness control. It can coat over 3D objects (Fig. A) or over ledges (Fig. B). For MDL, the first successful application of ALD was in the fabrication of ultra-high-performance anti-reflection coatings in UV. This application was ideal for ALD due to the wide variety of materials and the ability to precisely control film thickness in the nanometer range. The use of ALD to make these coatings led to detectors with world record external quantum efficiency in a wide range of the ultraviolet spectrum (100-300 nm) (Fig. C) and was featured as the cover art for the Jan/Feb 2013 issue of the Journal of Vacuum Science and Technology. Since then, ALD at MDL now includes superconducting films with sharp transition temperatures (Fig. D), passivating films for Sb-based detectors, mirror coatings, filters, batteries, and many others. The increasing numbers of materials and processes available via ALD continue to expand the importance of this processing technology, and it should continue to help MDL develop new instruments and components in the coming years.



● Fully packaged Cassini delta-doped CCD with ALD-deposited anti-reflection coating.

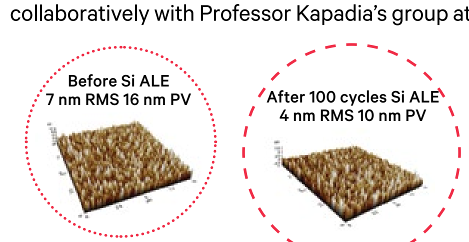
● Beneq TFS-200 atomic layer deposition system.



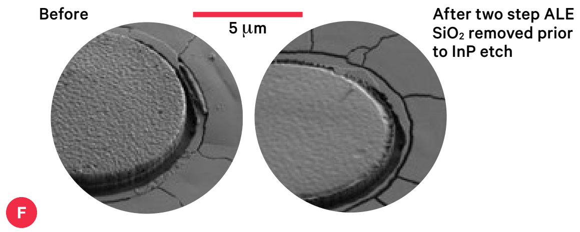
B ALD coating of InAs.

Atomic-Scale Processing: ALE Smoothing of III-V Materials. The advent of ALE has provided the final piece needed for complete atomic-scale processing. At MDL, a major use for ALE is to smooth films deposited via other techniques. For example, amorphous silicon (a-Si) is a dielectric material used for the fabrication of superconducting devices. The plasma-enhanced chemical vapor deposition process (PECVD) used to form the a-Si coating results in 7-nm roughness. The subsequent superconducting wiring layer is itself only 7 nm thick, which results in integration issues. When ALE is used to treat the a-Si, the coating is smoothed through the precise removal of 10 Å per cycle. ALE preferentially attacks protrusions from a surface, eventually achieving a final roughness of 1.9 nm (Fig. E). This technique has also been successfully applied to III-V semiconductors (Fig. F).

ALE-enabled smoothing of III-V materials found immediate application with a new class of devices grown on non-epitaxial substrates. Recently, in MDL's collaboration with USC, the team demonstrated high-electron-mobility single-crystal InAs mesas monolithically integrated on amorphous dielectric substrates at a growth temperature of 300°C. Critically, a room temperature mobility of ~5800 cm^2/V-s was measured, the highest mobility reported for any thin-film semiconductor material system directly grown on a non-epitaxial substrate. Detailed modeling of the scattering mechanisms in the grown material indicates that the mobility is limited by surface roughness scattering, not the intrinsic material quality. Reducing the RMS roughness of the InAs from 1.8 nm to 1 nm is projected to produce materials with room temperature mobilities of >10,000 cm^2/V-s, and 0.5-nm RMS would result in a ~20,000 cm^2/V-s mobility, essentially identical to epitaxially grown materials. These results pave the way for growth of high-mobility materials directly on the back end of silicon complementary metal-oxide-semiconductor (CMOS) wafers, as well as other non-epitaxial substrates, such as glass, and polymers for flexible electronics. This work, funded by the JPL Strategic University Research Partnership, is targeted toward science-grade monolithic short-wave infrared (SWIR) detectors grown directly on CMOS readouts, but it has potential use in a wide variety of optoelectronic devices, sensors, and active elements of interest. The work was conducted collaboratively with Professor Kapadia's group at USC.



E After 220 cycles of Si ALE.



F Atomic layer etch to smooth inp mesa.

ALE for Optoelectronic Devices. There is an increasing need to reduce the waveguide/resonator loss in laser applications (to increase the coherence and reduce the threshold), sensors (to improve the detection limit), and nonlinear photonics. A key source of loss in photonic components is the surface roughness. MDL's ALE processes could be a breakthrough for the creation of ultra-low-loss photonic waveguides, resonators, and other components. In another MDL collaboration with USC, the team is working on low-scattering-loss structures bonded with III-epitaxial films to realize highly coherent semiconductor lasers with Hz-level linewidths that can be used in fast coherent imaging and sensing applications. Moreover, we plan to use this ALE recipe to fabricate structures that will test the physics of thermalization of light in multimoded cavities and can be used as a new approach for spectrum cleaning and manipulation. The team's aim is to fabricate silicon nitride ring resonators with quality factors on the order of 200 million (limited by the material absorption loss). This would be a fivefold enhancement over the state of the art, which would enable the new classes of devices we seek to fabricate. For integrated III-V structures, the team plans to fabricate various micro- and nano-lasers to measure the light-light curve, threshold, and linewidth. For Si_3N_4 waveguides, the dispersion properties (anomalous versus normal) and hence the application in nonlinear photonics highly depend on the waveguide thickness and width, while loss determines the efficiency of the nonlinear mechanism in the actual settings. This work benefitted from collaboration with Professors Kapadia and Khajavikhan of USC.

Atomic-scale processing has been and continues to be a critical thrust area for MDL. The ability to grow, pattern, deposit, and etch with this level of control is important now and in the future as MDL continues to invent, develop, and deliver new technologies and microdevices.

2019 Highlights.

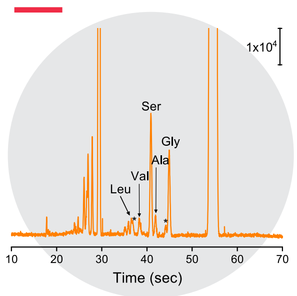
The team achieved room temperature mobility for InAs of ~5800 cm2/V-s, the highest mobility reported for any thin-film semiconductor material system directly grown on a non-epitaxial substrate. They also demonstrated a nearly fourfold reduction in roughness for a-Si devices and significant reductions for metals and II-V semiconductors with ALE.

in situ instruments

Chemical analysis & life detection

The engineers and scientists at MDL working in the area of Chemical Analysis and Life Detection are pioneering the next generation of spaceflight technologies needed in the search for habitable environments and life beyond Earth.

Biosignatures in the Atacama Desert.



The Life Detection and Chemical Analysis Group is so named to highlight its unique capabilities in analytical chemistry and instrument development. In 2019, Dr. Peter Willis became its supervisor. While the official group is relatively new, Dr. Willis has been leading a team of chemists and engineers at MDL for the past 10 years.

The focus of the group has been on the design of portable instrumentation for in situ chemical analysis. One of the major achievements for this competency was developing the Chemical Laptop, a truly portable, battery-powered, automated, and reprogrammable analysis system that uses a technique called capillary electrophoresis (CE). CE is a liquid-based separation technique, and the Chemical Laptop uses a miniaturized version, microchip electrophoresis (ME). ME can be coupled to a variety of detection modes, including laser-induced fluorescence (LIF). With this technology, the Chemical Laptop is the first "end-to-end" ME-LIF astrobiology instrument capable of receiving a liquid sample and performing all operations required for analysis in an automated fashion. This system would provide the sample processing capabilities required for in situ analysis with sub-parts-per-billion sensitivity in a compact, low-mass, and low-power package. This instrument concept could be adapted for a variety of astrobiologically interesting targets like Europa, Enceladus, or Titan. It also serves as a general prototype that could be reprogrammed for Earth-based analyses.

Much of the group's work has focused on developing a prototype for future astrobiology missions. The basic philosophy is that through detection of ionizable organic molecules, specific patterns in the size and type of the species in a sample can be used to indicate the presence of either biotic or abiotic chemistry. These molecules can be analyzed via CE, which can be coupled to a variety of detection modes, including LIF for parts per trillion (ppt) limits of detection, mass spectrometry (MS) for identification, and capacitively coupled contactless conductivity (C4D) for universal detection of ionic species. Using these three detection modes, the team can search for several key classes of organic molecules that are the building blocks of proteins, cell membranes, and DNA, as well as metabolites.

In 2019, the group was focused on an internally funded JPL program called JNEXT. The project, called Ocean Worlds Life Surveyor (OWLS), is an instrument suite that combines The Life Detection and Chemical Analysis Group's CE analyzer, including all three detection modes, with a holographic microscope being developed by another team at JPL. OWLS is a unique instrument suite, and the powerful combination of chemical analysis and microscopy has yet to be explored in the astrobiology community. In the coming years, the group hopes to use OWLS to analyze ocean world analogs on Earth to help understand and define what constitutes a biosignature and to better prepare JPL for future missions to targets like Europa and Enceladus.

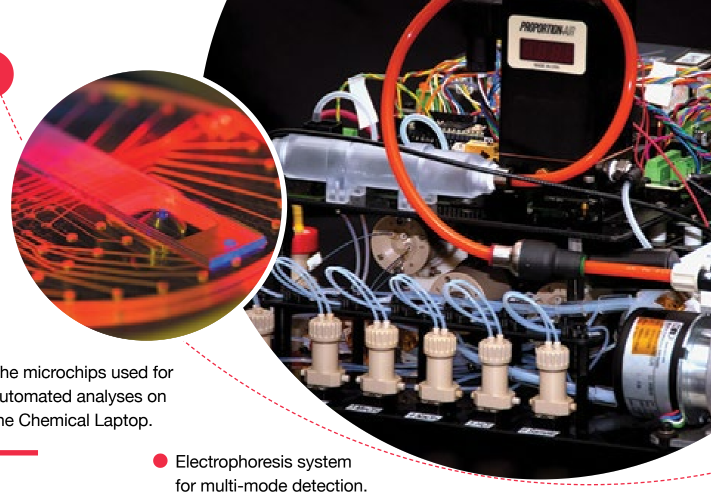
This year the team performed the first true end-to-end validation of a CE instrument suite in a Mars mission scenario.

Technologies of the Future

In 2019, two exciting achievements came during field tests with the team's portable instruments. In July, the OWLS team took their CE and microscope subsystems to the Kerckhoff Marine Laboratory in Newport Beach, California. There, samples of ocean water were collected daily and analyzed for both organic biosignatures and cell motility. This was the first time many of the instruments, including the portable, automated CE instrument designed and built by Dr. Konstantin Zamuruyev, were tested in the field. During the field campaign, the prototype was coupled to commercial MS and C4D systems, and low levels of organics were detected in the ocean water. This subsystem, along with the CE-LIF subsystem and data from the microscope, was used to detect life! This was a major milestone for the OWLS project and marked the beginning of the transition from the breadboard to the brass-board phase of development.

Work done in the lab by Dr. Jessica Creamer helped answer questions regarding the stability of the chemical reagents used for chiral amino acid analyses. Her project was to determine the limitations of long-term storage on the fluorescent dye needed to achieve ppt limits of detection with CE-LIF. The resulting publication in Electrophoresis showed that even after two years at elevated storage temperatures, the CE-LIF assay was not affected; thus, the science goals needed to detect life can be achieved.

The other major field test happened in September, when Drs. Fernanda Mora and Florian Kehl performed a simulated Mars mission in the Atacama Desert of Chile. Here, Dr. Mora demonstrated the Chemical Laptop. With a single operator command, the instrument could accept a liquid sample and perform fluorescence labeling and analysis in a truly automated fashion. This system was coupled to Dr. Kehl's portable subcritical water extractor, which had been demonstrated for remote operation in the field a year earlier, with results published in Earth Space Science. The instruments were mounted on a rover and operated remotely in the desert. End-to-end operation was demonstrated by analyzing soil samples that the rover delivered to the instrument. This was the first demonstration of automated "soil-to-data analysis." This validation was a critical milestone in advancing this technology for future implementation on a spaceflight mission.



The microchips used for automated analyses on the Chemical Laptop.

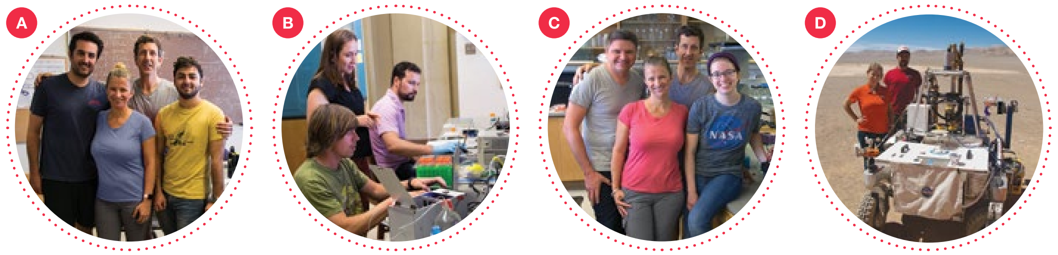
Electrophoresis system for multi-mode detection.

Additionally, Dr. Aaron Noell and postdoctoral researcher Dr. Elizabeth Jaramillo have developed miniature, solid-contact-based ion selective electrodes (ISEs). These next-generation sensors can now be incorporated into microfluidic instruments, such as OWLS and the Microfluidic Icy-World Chemical Analyzer (MICA), a miniaturized version of the Wet Chemistry Lab instrument that flew on the Mars Phoenix Lander mission.

The group is fortunate to be working with several NASA centers on a variety of projects, including an ICEE-2 grant with NASA Goddard; NASA Ames; Honeybee Robotics Ltd.; Dannel Consulting Inc.; and the University of Versailles, Saint-Quentin/LATMOS in France. The project is called the "Europan Molecular Indicators of Life Investigation" (EMILI). The group is also collaborating with AMES on two additional projects, a ColdTech grant called "SPLICE" and MICA, which is another ICEE-2. The Life Detection and Chemical Analysis Group is also working with several industrial partners such as SCIEX, VICI-Valco, and Leiden Technology.

The team's partnership with the University of Kansas (KU) also grew in 2019. In addition to the Willis group's KU graduates Dr. Creamer and postdoctoral researcher Dr. Nathan Oborny, Emily Kurfman, a graduate student, joined the group and performed some of the very first characterization work on our first portable system capable of performing mass spectrometry detection. Following her summer internship, Emily received a 3-year PhD grant through the NASA NSTGRO20 program and will be pursuing her PhD in a research program jointly designed by JPL and KU. Finally, to formalize the connection between the two institutions, and in particular the research group of Professor Susan Lunte, Dr. Willis was invited to join KU as an adjunct faculty member.

A B C D

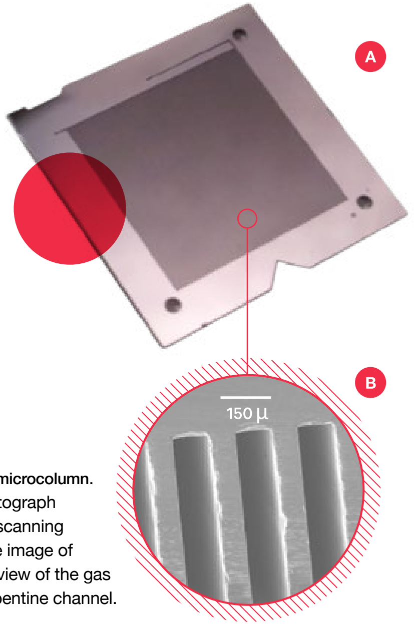


Members of the Chemical Analysis and Life Detection Group and collaborators during field trips to Newport Beach (**A-C**) and Chile's Atacama Desert (**D**). From left to right: Florian Kehl, Fernanda Mora, Peter Willis, Vlad Cretu; Coleman Richdale, Elizabeth Jaramillo, Mauro Santos; Konstantin Zamuruyev, Fernanda Mora, Peter Willis, Emily Kurfman; Fernanda Mora, Florian Kehl.

in situ instruments

Mass spec-trometry

NASA has included mass spectrometers in the payloads of many planetary missions for in situ analysis. Developments at MDL have found a completely different application for these devices: checking the quality of the cabin air for human spaceflight.



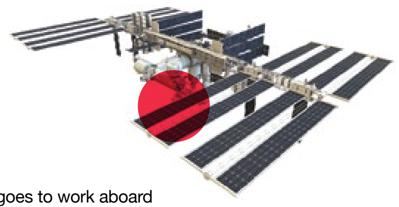
Gas chromatograph microcolumn. (**A**) JPL gas chromatograph microcolumn; (**B**) a scanning electron microscope image of the cross-sectional view of the gas chromatograph serpentine channel.

Members of the Vehicle Cabin Atmosphere Monitor team, from left: Ara Chutjian, Dan Karmon, Jim Hofman, Benny Toomarian, Murray Darrach, John MacAskill, Stojan Madzunkov, Arvid Croonquist, and Richard Kidd.

Originally, two competing approaches to making miniature mass spectrometers potentially suitable for spaceflight were being developed independently in the JPL Science Division: magnetic sector devices and quadrupole analyzers. These two efforts coalesced and were brought into MDL in November 2017. MDL was a good home for the technology, as it gave even readier access to MDL's microfabrication facilities.

JPL's miniature Quadrupole Ion Trap Mass Spectrometer (QITMS) has been evolving at JPL since 1994, and in that time, it has enjoyed a history of constant performance improvements and successively smaller size, mass and power requirements. It started development for human spaceflight applications in 2003 and for planetary applications in 2011. The first flight instrument to incorporate a QITMS was the Vehicle Cabin Atmospheric Monitor (VCAM), which operated successfully on the International Space Station (ISS) from March 2009 to November 2011. Its successor is the Spacecraft Atmosphere Monitor (SAM). The SAM instrument is a highly miniaturized gas chromatograph/mass spectrometer (GC-MS) that depends on MDL-fabricated components and monitors the atmosphere of crewed spacecraft for both trace organic compounds and the major constituents of the cabin air. The first version of the SAM instrument, which lacked the GC, was launched to the ISS in 2019. The complete second version will be launched in 2020. The future aim is to successfully produce an instrument for planetary scientific investigations, and first steps have been taken in that direction with the selection of the Lunar CubeSat Mass Spectrometer for development under the NASA Development and Advancement of Lunar Instrumentation (DALI) program (see page 26).

The QITMS as the core of an instrument is very versatile and can be configured in many different ways depending on the specific application. Samples are analyzed as gases; however, the mass spectrometer can be interfaced very easily to many different sample preparation for introduction systems if the analyte is not a gas initially. The QITMS possesses very high sensitivity and can make very precise measurements. It can measure both the concentrations and isotopic compositions of the full range of inorganic species. For example, it has measured the isotopic compositions of krypton and xenon accurately and to a precision of less than 0.1%. It can also quantify the amounts of much larger organic molecules, such as those that form the building blocks of life, an essential capability in undertaking astrobiology investigations.



SAM goes to work aboard the International Space Station.

The SAM instrument.

The QITMS is held in compression between two vacuum flanges enabling a robust, compact flight instrument.

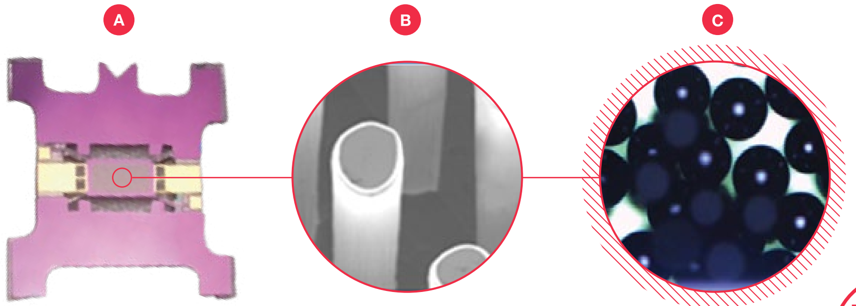
Spacecraft Atmosphere Monitor: Next Generation Gas Chromatograph Mass Spectrometer. The SAM consists of the miniature QITMS interfaced with a micro-fabricated preconcentrator and gas chromatograph unit (together forming the PCGC subassembly) and a small gas carrier reservoir. All these components were designed, fabricated, assembled and tested at MDL. The micro-fabricated PCGC unit employs a novel MEMS PCGC technology that is implemented by combining a MEMS preconcentrator, a microvalve and gas chromatograph chips that replace the macro PCGC components in the VCAM. This significantly reduces the total volume and mass of the GC-MS instrument from 64.4 L and 37.9 kg (VCAM) to 10 L and 9.5 kg (SAM).

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

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

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

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

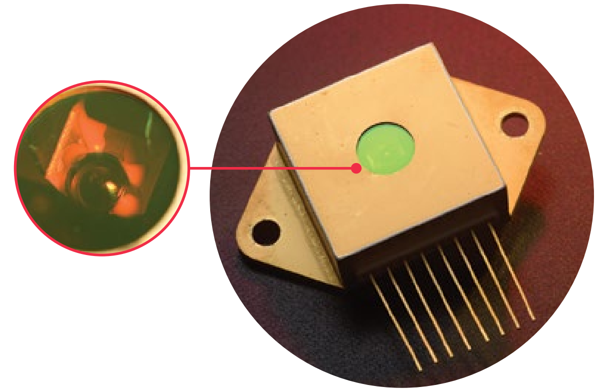


(**A**) Thermally isolated silicon heater in the middle chamber where Carboxen adsorbent particles are packed; (**B**) microposts for attaching micro/nano adsorbents; (**C**) Carboxen 1000 particles to be packed into the middle chamber that has no micropost.

in situ instruments

Tunable laser spectrometers

Over the past 30 years, MDL's core competency in the design and fabrication of semiconductor lasers has supported the development of several laser-based instruments, especially in situ laser spectrometers using novel infrared semiconductor laser sources.



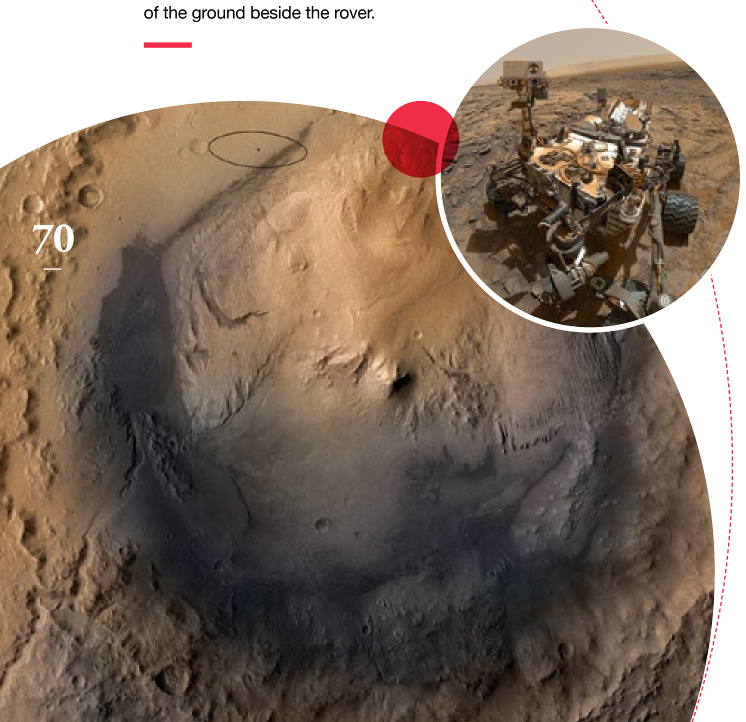
A hermetically sealed package designed to house MDL mid-infrared semiconductor lasers, including the lasers to be used for the Venus Tunable Laser Spectrometer.

Laser-Based Instruments. Laser absorption spectroscopy enables precise measurements of the abundance and isotopic composition of specific molecules. Deployable laser spectrometer instruments help scientists understand the structure and dynamics of planetary atmospheres and the chemical composition of gases evolved from rocks and ice. In addition to providing cutting-edge laser technology to instrument builders at JPL and elsewhere, MDL researchers have applied their expertise in optical systems, electronics, and spectroscopic techniques to build complete laser-based instruments for a range of environmental monitoring applications.

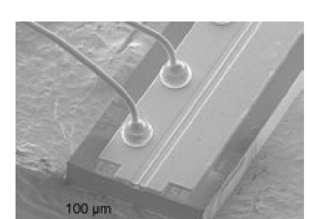
As an example of what can be achieved at JPL through the development of novel semiconductor laser technologies, MDL created the 3.3 µm wavelength semiconductor laser at the heart of the Tunable Laser Spectrometer (TLS). TLS is part of the scientific payload of the Curiosity rover, which launched in November 2011 and landed on Mars in August 2012. Curiosity has been working ever since and has produced remarkable and unexpected scientific results (see page 18). In particular, the 3.3 µm laser built by MDL has enabled measurements of methane at part-per-billion levels and continues to revolutionize our understanding of the atmosphere of Mars.

Looking to the future, MDL researchers continue to build on this competency in semiconductor lasers, enabling measurements with new lasers and instruments to better understand our solar system and even help humans venture beyond low Earth orbit.

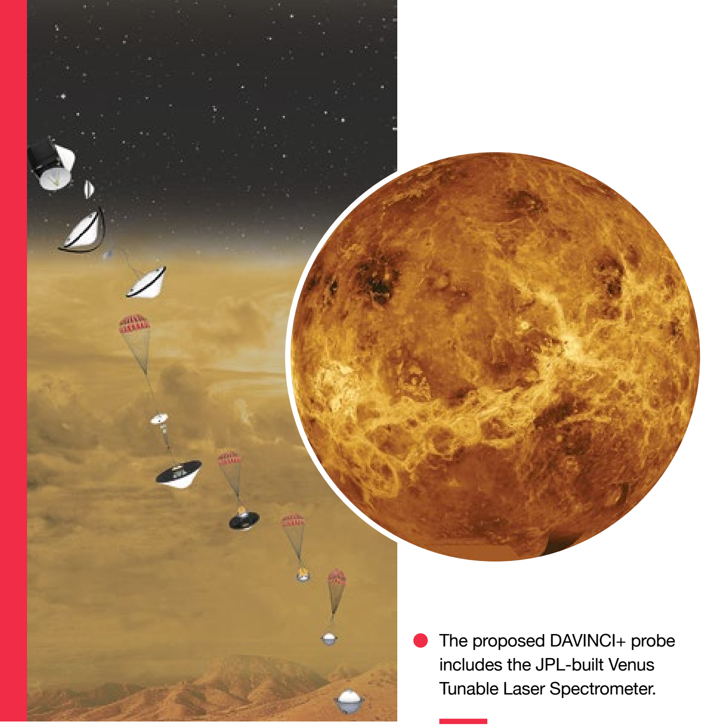
This self-portrait of the Mars rover Curiosity combines dozens of exposures taken on Mars (Feb. 3, 2013), plus three exposures taken during Sol 270 (May 10, 2013) to update the appearance of part of the ground beside the rover.



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



An electron micrograph of a low-power consumption quantum cascade laser fabricated at MDL for the Venus Tunable Laser Spectrometer instrument.

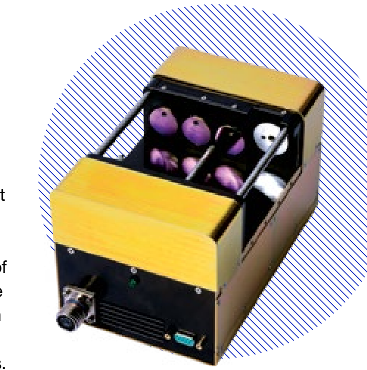


The proposed DAVINCI+ probe includes the JPL-built Venus Tunable Laser Spectrometer.

Venus Tunable Laser Spectrometer. The DAVINCI+ mission is one of four missions recently selected by NASA as a finalist for the agency's Discovery Program for solar system exploration. The DAVINCI+ team proposes to drop a descent probe through the atmosphere of Venus to study the composition of the planet's hot, dense cloud layers. A critical component of the DAVINCI+ instrument suite is the JPL-built Venus Tunable Laser Spectrometer (VTLS), which measures the concentration and isotopic composition of several specific compounds that are key to the climate cycles of Venus. The data gathered by VTLS will improve our understanding of not only Earth's nearest planetary neighbor but also Venus-like exoplanets, and even Earth itself at a different time in its evolution. In advance of the DAVINCI+ mission, MDL has developed mid-infrared quantum cascade lasers that can probe carbonyl sulfide and sulfur dioxide molecules to quantify sulfur isotope ratios. These lasers have watt-level power consumption, and they have been tested and shown to withstand the mechanical shock and thermal cycling expected inside the DAVINCI+ probe.

The JPL Project Element Manager for VTLS is former MDL Director Christopher Webster. The VTLS Instrument Lead is MDL engineer Ryan Briggs, and the quantum cascade lasers for VTLS were developed by MDL engineers Clifford Frez, Mathieu Fradet, and Ryan Briggs.

The ventilator prototype for coronavirus disease patients designed and built by NASA's JPL in southern California.



The Combustion Product Monitor instrument was delivered for NASA's Saffire project, a series of experiments to study the dynamics of combustion events in low-gravity spacecraft environments.

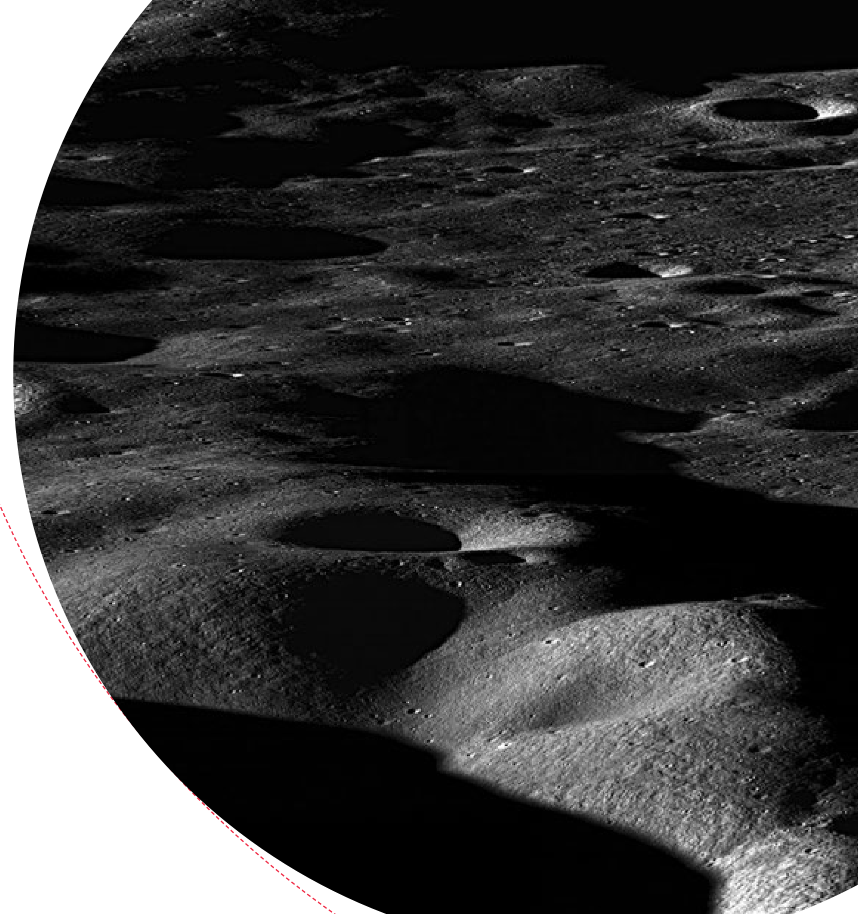
Combustion Product Monitor. The CPM instrument is a laser absorption spectrometer built by MDL in support of the Spacecraft Fire Safety Demonstration Project (Saffire), led by the NASA Glenn Research Center. CPM measures ambient gas-phase concentrations of six specific compounds related to combustion events in spacecraft environments, enabling early detection of accidental fires as well as safe post-fire cleanup during human spaceflight operations. The final version of the CPM instrument has a mass of 2.3 kg, a volume of 3.3 L, and a steady-state power consumption of 12 W. As part of the Saffire project, the CPM instrument will measure the mixing and evolution of emissions from a combustion event in microgravity aboard a Cygnus automated cargo spacecraft after leaving the International Space Station. In early 2020, engineers from MDL delivered a CPM instrument for integration with the Saffire VI experiment, which is expected to be operational in 2021.

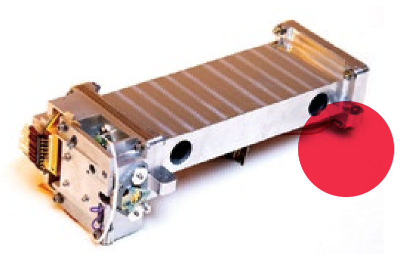
In support of future fire safety experiments, MDL is currently developing a compact three-channel laser spectrometer, Mini-CPM, to measure concentrations of carbon monoxide, carbon dioxide, and oxygen with even higher accuracy than that of the standard CPM instrument. The miniaturized instrument can also be operated in either an open or sealed configuration, allowing for ambient measurements or in-line monitoring of gas streams. The instrument volume is 0.5 L, more than six times smaller than the six-channel CPM.

Amid the global coronavirus pandemic, the CPM flight spare for Saffire was repurposed to test the JPL emergency COVID-19 ventilator, VITAL. The CPM instrument's high-dynamic-range, accurate oxygen detection capability has enabled leak-rate testing and validation of oxygen enrichment in the gas mixtures generated by the VITAL ventilator.

The CPM project is managed by MDL engineer Ryan Briggs. The CPM instruments for Saffire were built and tested by MDL engineer Mathieu Fradet. MDL technologist Nicholas Tallarida is designing the prototype Mini-CPM instrument. The overall project's Principal Investigator is David Urban, Branch Chief at the NASA Glenn Research Center.

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 in situ extraction of oxygen propellant and other resources needed for sustained human presence on the lunar surface.





The baseline design of the Laser In situ Resource Analyzer is based on the Mars MiniTLS methane instrument developed by Erik Alerstam and Christopher Webster. To monitor trace water levels in oxygen propellant streams, the LIRA design includes a new laser source to target water absorption lines and high-pressure flow seals.

Laser In Situ Resource Analyzer. As NASA pushes toward a sustained human presence on the Moon, return trips from the lunar surface will depend on the ability to refuel ascent vehicles using stored propellants. The dream of In Situ Resource Utilization (ISRU) is dependent upon the development of technologies that can be used to extract and process useful materials from the lunar environment. A major component of ISRU operations will be extraction and storage of cryogenic oxygen propellant from water ice and other regolith materials using chemical reduction processes. Propellant-grade oxygen must be extremely dry, with water contamination on the order of a single part per million; therefore, NASA needs sensors capable of both operating in the harsh environment of the lunar surface and reliably validating propellant purity at these stringent levels.

Laser spectrometers are not only capable of achieving the sensitivity required for trace contamination measurements, but, as shown with the JPL-built TLS instrument operating on the Mars Curiosity rover for more than seven years, the technology is also robust enough for extended operations in harsh space environments. The Laser In situ Resource Analyzer (LIRA) is a laser spectrometer under development at MDL with support from the NASA Game Changing Development Program. The LIRA sensor will be capable of continuously monitoring trace water levels in oxygen propellant streams over a broad range of flow pressures and temperatures. Initial LIRA demonstration units will be delivered to the NASA Johnson Space Center in 2022 for integration into ISRU propellant testbeds.

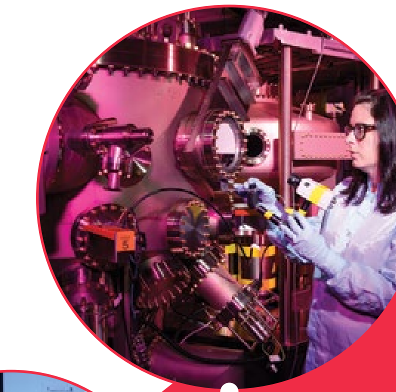
The LIRA project is managed by MDL engineer Ryan Briggs. The LIRA team includes MDL engineers Nicholas Tallarida and Mathieu Fradet, as well as Lance Christensen and Christopher Webster from the JPL Science Division and Erik Alerstam from the JPL Flight Communication Systems Section.

Semiconductor Laser Frequency Combs. Interband Cascade (IC) structures offer attractive potential for enabling both broadband coherent optical sources of mid-infrared light and fast photodetectors at room temperature. Recently, MDL researchers have demonstrated a compact broadband spectrometer based on co-integration of two free-running ICL comb devices with near-THz-wide spans and an IC-based photodetector with several GHz of electrical bandwidth. The spectrometer system was used to measure 1,1-difluoroethane over 600 GHz of optical coverage around 3.6 µm. This work demonstrates a chip-based instrument enabling the measurement of high-resolution spectra of broadband hydrocarbons in the mid-infrared range without the need for moving parts. The spectrometer is the first demonstration of a compact dual-comb system that enables broadband fast interrogation of the environment. Furthermore, MDL is expanding its inventory of comb devices to cover other spectral regions in the 2- and 8-µm spectral bands, which not only allows measurements of a broader collection of molecules but also has applications in high-data-rate optical communication and high-angular-resolution imaging of stars and satellites.

The effort to develop semiconductor laser frequency combs is led by MDL engineer Mahmood Bagheri. Fabrication of frequency comb devices is performed by MDL engineer Clifford Frez, and system design and characterization are performed by MDL postdoctoral scholar Lukasz Sterczewski.

Facility & capabilities

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



DEPOSITION

ETCHING

CHARACTERIZATION

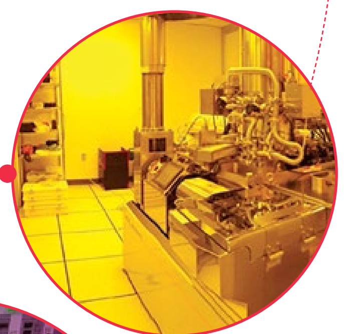
PACKAGING

The 30th anniversary of full operations at MDL is an opportunity to reflect on how MDL's facility infrastructure and equipment capabilities have evolved to support its technology advances. The Base Building's original design was sound, but it has since morphed to meet changing demands.

MDL's equipment capabilities and operations have changed based on the need to improve controls across larger wafers. By controlling the energetics of impinging ions for etching and depositions; improving uniformity, cleanliness, sidewall smoothness and coverage; and using atomic-level precision, MDL's staff has been able to manipulate electromagnetic fields to enable new observables and generate greater scientific returns in instrumentation.

For example, the use of global cleanrooms instead of microenvironments enables flexibility as processes change and accommodates multiple processes in one space. Our technology developments are diverse: the use of multiple material families (Si, GaAs, GaSb, and superconducting materials) allows detector contributions ranging from soft X-rays to mm wavelengths. Consequently, wafers in a range of sizes and thicknesses, along with compatible equipment, are needed.

Our equipment investments also continue to evolve. Thanks to premier achievements in greyscale grating fabrications, our e-beam lithography investments continue, most recently with the installation of the third upgraded replacement system in 2018. 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 RIEs to ICP RIEs, then to deep silicon etching (DRIE) and, most recently, atomic layer etching (ALE). Deposition system investments are also evolving: LPEs were replaced by MOCVDs, which were then replaced by MBE super lattice growth capabilities for the fabrication of semiconductor lasers.


PATTERNING


SAMPLE PREPARATION

The Tystar LPCVD capability to grow silicon rich low stress silicon nitride membranes was upgraded for larger wafers. Our MBE capabilities include a unique silicon MBE with UHV evaporation capabilities for 200 mm (8 inch) diameter wafers, enabling delta-doped UV CCDs.

Additionally, we have invested in III-V (Sb) MBE wafer processing technologies that allow NIR, MIR, and LWIR FPAs and a HOT BIRD design that can operate at higher cryo temperatures. We are also expanding our Atomic Layer Deposition (ALD) capabilities. We are currently fabricating a new ALD/metal evaporator system that will soon join our two existing systems. Advances in characterization include a new cold cathode Scanning Electron Microscope (SEM), atomic force microscopes (AFMs), X-ray diffraction, an upgraded XPS system, an extended range ellipsometer, FTIR capabilities, and a 1.7 K cryo probe station.

We plan on continuing our larger-diameter wafer processing capabilities via a lift-off and photoresist removal tool, replacing existing solvent and acid wet processing stations with stations capable of processing cassettes of larger (150 mm/6 inch diameter) wafers, and improving particle control to improve yields for large-area deliverables. We would like to retain some systems with no material constraints, as these systems would allow for testing of new materials and techniques, but footprint constraints limit these options.

MDL's infrastructure has also been maintained and improved. The machine shop was converted into a microfluidic processing lab in 2001. Cross-disciplinary successes permitted the addition of an annex to the Base Building in 2004. This annex became home to the "light lab" testing laboratories, and the cleanrooms, whose footprints were very limited, were then expanded into the former light lab space on the north side of the first floor. This cleanroom expansion continues today.

Humidity control systems were upgraded in 2001, 2006, and 2012, and AH5 and AH6 were added in 2000 for better control. In 2002, noise reduction measures were taken in AH1, and in 2009, variable speed drives were added to the cleanroom RCUs to save energy during off hours. Power upgrades include the addition of a 300 kVA transformer in 2000, 30 kW solar panels in 2008, a 45 kVA transformer in 2009, and a new replacement 500 kW emergency generator in 2012.

MDL received new process cooling water circulation pumps and filtration in 2009, and in 2010, the compressed dry air system was upgraded and backups were installed. The MDL DI/RO1 water plant was reconfigured to save water, and other upgrades followed with RO2 and RO3 additions in 2001 and 2003, respectively. Our safety monitoring system points have expanded, and the entire safety monitoring system has been upgraded and replaced over the course of four years: in 2000, 2007, 2011, and 2017. Finally, MDL's three original liquid nitrogen tanks and their distribution connections were replaced in 2019.

Future infrastructure improvements will include continued cleanroom conversions to allow more processing space, the installation of bypass electrical feeds to critical systems to minimize the effects of long maintenance shutdowns, and an improved ultra high purity (UHP) water supply from the MDL deionized water plant. A request for a replacement "MDL New Exploration Technologies" (MDL NExT) building has also been initiated.

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. Frank Greer, Central Processing Lead and Alternate Manager, has expertise in ALD and ALE. Matt Dickie (DRIE, LPCVD, SEM, sputtering, bonding, patterning), Chuck Manning (evaporations, etching, patterning), James Wishard (dicing), and Mike Fitzsimmons (patterning, packaging) provide semiconductor processing capabilities for those who do not want to utilize the facility directly. MDL Safety Engineers Mark Mandel, CIH (lead); Amy Posner; Michael Martinez; and Toney Davis provide safety assurance maintenance oversight, including life safety monitoring systems maintenance and chemical waste handling. Roopinderjit Bath, PE (lead); Ramzy Rizkallah; Chuck Manning; and Toney Davis provide MDL facilities maintenance and coordination. The MDL equipment is maintained and qualified by James Wishard (lead), Mike Fitzsimmons, Chuck Manning, Matt Dickie, and Frank Greer. Chuck Manning (lead), Frank Greer, Matt Dickie, Roopinderjit Bath, and Ramzy Rizkallah, together with input from knowledgeable MDL Processors, coordinate new equipment specifications and installations.

MDL's facilities, equipment and infrastructure capabilities were built on a solid foundation and were continuously updated to remain strong today. They have a bright future.

Within the MDL clean room fabrication areas, skilled and knowledgeable processors make use of sophisticated equipment to manipulate materials and structures on an atomic scale to create unique devices for obtaining new observables for the science community.

Appendices

Peer-Reviewed Journal Publications

1. Allmaras, J.P. et al. "Intrinsic Timing Jitter and Latency in Superconducting Nanowire Single-photon Detectors" Phys. Rev. Applied, Vol. 11, 034062 (2019)
2. Alonso-delPino, M., C. Jung-Kubiak, T. Reck, N. Llombart, and G. Chattopadhyay, "Beam Scanning of Silicon Lens Antennas Using Integrated Piezomotors at Submillimeter Wavelengths," IEEE Transactions on Terahertz Science and Technology, vol. 9, no. 1, pp. 47-54 (2019).
3. Avice, G, A. Belousov, K. A. Farley, S. M. Madzunkov, J. Simcic, D. Nikolić, M. R. Darrach, and C. Sotin, High-precision measurements of krypton and xenon isotopes with a new static-mode quadrupole ion trap mass spectrometer, Journal of Analytical Atomic Spectrometry, Vol. 34, 104-117 (2019).
4. Caloz, M. et al. "Intrinsically-limited timing jitter in molybdenum silicide superconducting nanowire single-photon detectors" Journal of Applied Physics, Vol. 126, 164501 (2019)
5. Chahat, N., E. Decrossas, D. Gonzalez-Ovejero, O. Yurduseven, M. J. Radway, R. E. Hodges, P. Estabrook, J. D. Baker, D. J. Bell, T. A. Cwik, and G. Chattopadhyay, "Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review," IEEE Antennas and Propagation Magazine, vol. 61, no. 5, pp. 37-46, (2019).
6. Chakrabarty, M. A. Lindeman, B. Bumble, A. W. Kleinsasser), W. A. Holmes, and D. Cunnane "Operation of YBCO Kinetic-Inductance Bolometers for Outer Solar System Missions" Appl. Phys. Lett. , Vol. 114, 132601 (2019).
7. Creamer, J. S., Mora, M. F., Noell, A. C., Willis, P. A., Long-term thermal stability of fluorescent dye used for chiral amino acid analysis on future spaceflight missions. Electrophoresis, Vol. 40 (23-24), 3117-3122 (2019,).
8. Frasca, S., B. Korzh, M. Colangelo, D. Zhu, A. E. Lita, J. P. Allmaras, E. E. Wollman, V. B. Verma, A. E. Dane, E. Ramirez, A. D. Beyer, S. W. Nam, A. G. Kozorezov, M. D. Shaw, and K. K. Berggren "Determining the depairing current in superconducting nanowire single-photon detectors" Phys. Rev. B, Vol. 100, 054520, (2019)
9. Gan, Y, B Mirzaei, JRG Silva, A Khalatpour, Q Hu, C Groppi, JV Siles, "81 supra-THz beams generated by a Fourier grating and a quantum cascade laser," Optics Express 27 (23), 34192-34203 (2019).
10. Jafari, Mohsen, L. Jay Guo, Mina Rais-Zadeh A Reconfigurable Color Reflector by Selective Phase Change of GeTe in a Multilayer Structure. Advanced Optical Materials, vol. 7 (5) (2019) https://doi.org/10.1002/adom.201801214
11. Kehl, F., Kovarik, N. A., Creamer, J. S., Da Costa, E. T., Willis, P. A., A subcritical water extractor prototype for potential astrobiology spaceflight missions. Earth and Space Science, Vol 6 (12), 2443-2460 (2019).
12. Kim, Y., Y. Zhang, T. Reck, D. J. Nemchick, G. Chattopadhyay, B. Drouin, M-C. F. Chang, and A. Tang, "A 183-GHz InP/CMOS-Hybrid Heterodyne-Spectrometer for Spaceborne Atmospheric Remote Sensing," IEEE Transactions on Terahertz Science and Technology, vol. 9, no. 3, pp. 313-334 (2019).
13. Mehdi, I, P Goldsmith, D Lis, J Pineada, B Langer, J Siles, J Kawamura, "Far-Infrared Heterodyne Array Receivers," Bulletin of the American Astronomical Society 51 (7) (2019).
14. Mora, M. F., Garcia, C. D., Schaumburg, F., Kler, P. A., Berli, C. L. A., Hashimoto, M.; Carrilho, E., Patterning and Modeling Three-Dimensional Microfluidic Devices Fabricated on a Single Sheet of Paper. Analytical Chemistry, Vol 91 (13), 8298-8303 (2019).
15. Nikolić, D, S.M. Madzunkov, M.R. Darrach, Response of QIT-MS to Noble Gas Isotopic Ratios in a Simulated Venus Flyby, Atmosphere, Vol. 10(5), 232 (21 pp) (2019).
16. Onstott TC, Ehlmann BL, Sapers H, Coleman M, Ivarsson M, Marlow JJ, Neubeck A and Niles P. Paleo-Rock-Hosted Life on Earth and the Search on Mars: a Review and Strategy for Exploration. Astrobiology, Vol. 19 1-33 (2019). DOI: 10.1089/ast.2018.1960
17. Pagano, Thomas S.; Carlo Abesamis; Andres Andrade; Hartmut H. Aumann; Sarath D. Gunapala; Cate Heneghan; Robert F. Jarnot; Dean L. Johnson; Andy Lamborn; Yuki Maruyama; Sir Rafol; Nasrat A. Raouf; David M. Rider; Dave Ting; Dan Wilson; Karl Y. Yee; Jerold Cole; Bill Good; Tom U. Kampe; Juancarlos Soto; Arn L. Adams; Matt Buckley; Richard Graham; Fred Nicol; Tony Vengel; John Moore; Thomas Coleman; Steve Schneider; Chris Esser; Scott Inlow; Devon Sanders; Karl Hansen; Matt Zeigler; Charles Dumont; Rebecca Walter; Joe Piacentine, "CubeSat Infrared Atmospheric Sounder technology development status", J. of Applied Remote Sensing, 13(3), 032512 (2019). https://doi.org/10.1117/1.JRS.13.032512
18. Pepper, B., A. Soibel, D. Ting, C. Hill, A. Khoshakhlagh, A. Fisher, S. Keo, S .Gunapala, Spatial dependence of carrier localization in InAsSb/InSb digital alloy nBn detector, Infrared Physics & Technology 99, 64-70, (2019). https://www.sciencedirect.com/science/article/abs/pii/S1350449518305073
19. Phan, HP, TK Nguyen, T Dinh, A Qamar, A Iacopi, J Lu, DV Dao, Wireless battery-free SiC sensors operating in harsh environments using resonant inductive coupling. IEEE Electron Device Letters, vol. 40 (4), 609-612 (2019)
20. Qamar, A, M Rais-Zadeh Coupled baw/saw resonators using AlN/Mo/Si and AlN/Mo/GaN layered structures. IEEE Electron Device Letters, vol. 40 (2), 321-324 (2019)

21. Qamar, A, S Sherrit, XQ Zheng, J Lee, PXL Feng, M Rais-Zadeh. Study of energy loss mechanisms in AlN-based piezoelectric length extensional-mode resonators. Journal of Microelectromechanical Systems, vol. 28 (4), 619-627 (2019)
22. Richard J. Roy, Matthew Lebsock, Luis Millán, Robert Dengler, Raquel Rodriguez Monje, Jose V. Siles, and Ken B. Cooper, "Boundary-layer water vapor profiling using differential absorption radar," Atmospheric Measurement Techniques, vol. 11, no. 12, pp. 6511-6523 (2018).
23. Soibel, Alexander, David Z. Ting, Sir B. Rafol, Anita M. Fisher, Sam A. Keo, Arezou Khoshakhlagh, and Sarath D. Gunapala, Mid-wavelength infrared InAsSb/InAs nBn detectors and FPAs with very low dark current density, Journal Reference: Applied Physics Letters 114, 161103 (2019), https://doi.org/10.1063/1.5092342
24. Sterczewski, L. A., J. Westberg, M. Bagheri, C. Frez, I. Vurgaftman, C. L. Canedy, W. W. Bewley, C. D. Merritt, C. S. Kim, M. Kim, J. R. Meyer, and G. Wysocki, "Mid-infrared dual-comb spectroscopy with interband cascade lasers," Optics Letters, vol. 44, 2113-2113 (2019). https://doi.org/10.1364/OL.44.002113
25. Sterczewski, L. A., M. Bagheri, C. Frez, C. L. Canedy, I. Vurgaftman, M. Kim, C. S. Kim, C. D. Merritt, W. W. Bewley, and J. R. Meyer, "Near-infrared frequency comb generation in mid-infrared interband cascade lasers," Optics Letters, vol. 44, 5828-5831 (2019). https://doi.org/10.1364/OL.44.005828
26. Theiling B and Coleman M. Paleo-microbial-ecology of the Monterey Formation: implications for Middle Miocene paleoclimatology. Mar. Geol. 413 112-128 (2019). https://doi.org/10. 10 l 6/j.margeo.20 l 9.04.001
27. Waller, SE, A. Belousov, R.D. Kidd, D. Nikolić, S.M. Madzunkov, J.S. Wiley, and M.R. Darrach, Chemical Ionization Mass Spectrometry: Applications for the In Situ Measurement of Nonvolatile Organics at Ocean Worlds, Astrobiology, Vol. 19(10), 1196-1210 (2019).
28. White, L.M., Shibuya, T., Vance, S., Christensen, L.E., Bhartia, R., Kidd, R.D., Hoffman, A., Stucky, G.D., Kanik, I. & Russell, M.J.. Simulating serpentinization as it could apply to the emergence of life using the JPL hydrothermal reactor. Astrobiology, Vol. 20, 307-326 (2019).
29. Wollman, E. E., V. B. Verma, A. E. Lita, W. H. Farr, M. D. Shaw, R. P. Mirin, and S. W. Nam "Kilopixel array of superconducting nanowire single-photon detectors. Opt. Express, Vol. 27 (24), 35279-35289 (2019)
30. Yurduseven, O., K. Cooper, and G. Chattopadhyay, "Point-Spread-Function (PSF) Characterization of a 340-GHz Imaging Radar Using Acoustic Levitation," IEEE Transactions on Terahertz Science and Technology, vol. 9, no. 1, pp. 20-26 (2019).
31. Zhu, Di, et al. "Superconducting nanowire single-photon detector with integrated impedance-matching taper" Appl. Phys. Lett. , Vol. 114, 042601 (2019)
32. Zobrist, N., B.H. Eom, P. Day, B.A. Mazin, S.R. Meeker, B. Bumble, H.G. LeDuc, G. Coiffard, P. Szypryt, N. Fruitwala, I. Lipartito, C. Bockstiegel "Wide-band parametric amplifier readout and resolution of optical microwave kinetic inductance detectors" Appl. Phys. Lett., Vol. 115, 042601 (2019)
33. Zobrist, Nicholas, Gregoire Coiffard, Bruce Bumble, Noah Swimmer, Sarah Steiger, Miguel Daal, Giulia Collura, Alex Walter, Clint Bockstiegel, Neelay Fruitwala, Isabel Lipartito, and Benjamin A. Mazin, "Design and Performance of Hafnium Optical Kinetic Inductance Detectors" Appl. Phys. Lett. , Vol 115, 213503 (2019); https://doi.org/10.1063/1.5127768

Conference Publications

1. Bagheri, M., Interband Cascade Frequency Comb Devices, IEEE Photonics Society Summer Topical Meeting Series (SUM) (Keynote), TuC4.1, Fort Lauderdale, FL, USA, July (2019)
2. Baines, K. H., J. A. Cutts, D. Nikolić, S. M. Madzunkov, M. L. Delitsky, S. S. Limaye, and K. McGouldrick, The JPL Venus Aerosol Mass Spectrometer Concept, Proceedings of the 16th International Planetary Probe Workshop, 8-12 July 2019, Oxford University, UK.
3. Baines, K.H., J.A. Cutts, D. Nikolic, S.M. Madzunkov, J.-B. Renard, O. Mousis, L.M. Barge, and S.S. Limaye, An Aerosol Instrument Package for Analyzing Venusian Cloud Particles, 17th Meeting of the Venus Exploration and Analysis Group (VEXAG), November 6-8, 2019 in Boulder, Colorado USA, LPI Contribution No. 2193, id.8010 (2019).
4. Baines, K.H., J.A. Cutts, D. Nikolic, S.M. Madzunkov, M.L. Delitsky, S.S. Limaye, K. McGouldrick, The JPL Venus Aerosol Mass Spectrometer Concept, 16th International Planetary Probe Workshop & Short Course titled • Ice Giants: Exciting Targets for Solar System Entry Probes Exploration • 6–7 July 2019 Oxford University
5. Bao, X, S Sherrit, CF Frez, V Scott, M Rais-Zadeh Analysis of performances of MEMS infrared sensor based on piezoelectric bending resonators ... Proceedings Volume 10970, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2019; 1097028 (2019) https://doi.org/10.1117/12.2514440
6. Boieriu Paul; Christoph Grein; Christopher Buurma; Jered Feldman; Richard Pimpinella; Anthony Ciani; Alexander Soibel; David Z. Ting, Inductively coupled plasma hydrogenation of LWIR type-II superlattices, March 2019 Proceedings of SPIE — The International Society for Optical Engineering XVI (109260I):17
7. Briggs, Ryan M., Mathieu Fradet, Clifford Frez, Kevin He, Romain Blanchard, Laurent Diehl, and Christian Pflügl, Quantum cascade lasers for in situ planetary science spectrometers, IEEE Photonics Conference, 2019. (invited)
8. Chattopadhyay, G., A. Tang, M. Alonso del-Pino, C. Jung-Kubiak, J. Kooi, J. Siles, and C. Lee, Highly Integrated Submillimeter-Wave Spectrometer for CubeSats, Proc. 44th International Conference on Infrared, Millimeter, and THz Waves, Paris, France, September 2019.
9. Chattopadhyay, G., Cryogenic Sensors and Other Terahertz Technologies for Science Applications, Indian Conference on Antennas and Propagation (InCAP), Ahmedabad, India, December 2019.
10. Chattopadhyay, G., M. Alonso-delPino, and J. Kooi, Antennas, Arrays, and Systems for Submillimeter-Wave Radio Astronomy, Proc. 13th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, April 2020.
11. Chattopadhyay, G., Packaging and Integration Solutions at Terahertz Frequencies, Proc. MTT-S International Microwave Symposium, Boston, MA, June 2019.
12. Chattopadhyay, G., Science Instruments for CubeSats and SmallSats, European Microwave Week, Paris, France, September 2019.
13. Chen, Christine P., Darren Hayton, Cecile Jung-Kubiak, Joseph Lee, Jose Siles, Maria Alonso, Alex Peralta, Imran Mehdi, Designing and Fabricating a Three-Dimensional Silicon Stack for a 2.06 THz Receiver Front End, Postdoc Research Poster Session, T-12, presented on July 10, 2019, Pasadena, CA.
14. Chen, Christine P., Darren Hayton, Robert Lin, Cecile Jung-Kubiak, Jose Siles, Choonsup Lee, Maria Alonso, Alex Peralta, Imran Mehdi Design and Fabrication of Silicon Stacked Architecture for 2.06 THz Receiver Front End,, ISSTT Proceedings by NRAO, submitted June 28, 2019.
15. Chen, Christine P., Darren Hayton, Robert Link, Cecile Jung-Kubiak, Jose Siles, Choonsup Lee, Maria Alonso, Imran Mehdi Design and Fabrication of Silicon Stacked Architecture for 2.06 THz Receiver Front End,, International Symposium on Space Terahertz Technology, presented on April 15, 2019, Gothenberg, Sweden.
16. Cooper, Ken B., Richard J. Roy, Jose V. Siles, Matthew Lebsock. Luis Millan, Omkar Pradhan, and Raquel Rodriguez Monje, Differential Absorption Radar at 170 and 560 GHz for Humidity Remote Sensing, Proc. SPIE, 2020.
17. Cortez, A. T., E. Y. Cho, H. Li, D. Cunnane, B. Karasik, and S. A. Cybart, Tuning Y-Ba-Cu-O focused helium ion beam Josephson junctions for use as THz mixers, IEEE Trans. Appl. Supercond., 29(5), 1102305 (2019).
18. Cortez, A., E.Y. Cho, H. Li, D. Cunnane, B. Karasik, S.A. Cybart, High-Frequency Properties of Y-Ba-Cu-O Josephson Junctions Fabricated with Helium Ion Beam Irradiation, 2019 IEEE Int. Supercond. Electron. Conf. (ISEC), DOI: 10.1109/ISEC46533.2019.8990898
19. Goldsmith, P., Y Seo, D Lis, J Siles, W Langer, J Kawamura, Source-A Space Mission to Probe the Trail of Water, 2019 44th International Conference on Infrared, Millimeter, and Terahertz
20. Goldsmith, Paul, Dariusz Lis, Jon Kawamura, Jose Siles and Youngmin Seo,THz Space Mission to Probe the Trail of Water, Int, Symp, on Space THZ Technology, 2020
21. Goldsmith, Paul, Youngmin Seo, Dariusz Lis, Jose Siles, William Langer, & Jon Kawamura, Source – A Space Mission to Probe the Trail of Water, 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW) 2019 September 1-6
22. González-Ovejero, C., A. Mahmoud, X. Morvan, M. Ettorre, R. Sauleau, S. Maci, G. Chattopadhyay, and N. Chahat, Metal-Only Modulated Metasurface Antenna for CubeSat Platforms, Proc. IEEE International Symposium on Antennas and Propagation, Atlanta, GA, USA, July 2019.
23. González-Ovejero, D., M. Faenzi, A. Mahmoud, M. Ettorre, R. Sauleau, N. Chahat, G. Chattopadhyay, and S. Maci, Some Recent Developments on Modulated Metasurface Antennas, IEEE International Microwave and RF Conference (IMaRC), Mumbai, India, December 2019.
24. Gunapala Sarath; Sir Rafol; David Ting; Alexander Soibel; Arezou Khoshakhlagh; Sam Keo; Brian Pepper; Anita Fisher; Edward Luong; Cory Hill; Kwong-Kit Choi; Arvind D'Souza; Christopher Masterjohn; Sachidananda Babu; Parminder Ghuman Infrared Digital Focal Plane Arrays for Earth Remote Sensing Applications, 2019 IEEE Photonics Conference (IPC), San Antonio, TX, USA, 2019, pp. 1-2. DOI: 10.1109/IPCon.2019.8908367
25. Gunapala, Sarath, Sir Rafol, David Ting, Alexander Soibel, Arezou Khoshakhlagh, Sam Keo, Brian Pepper, Anita Fisher, Cory Hill, Kwong-Kit Choi, Arvind D'Souza, Christopher Masterjohn, Sachidananda Babu, Parminder Ghuman, Proc. SPIE 11129, Infrared Sensors, Devices, and Applications IX, 111290C (9 September 2019); https://doi.org/10.1117/12.2533477
26. Gunapala, Sarath; David Ting; Alexander Soibel; Arezou Khoshakhlagh; Sir Rafol; Cory Hill; Anita Fisher; Brian Pepper; Kwong-Kit Choi; Arvind D'Souza; Christopher Masterjohn; Sachidananda Babu; Parminder Ghuman, Antimonides Type-II superlattice digital focal plane arrays for Space remote sensing instruments, SPIE Proceedings 11180, International Conference on Space Optics — ICSO 2018; 111803T (2019) https://doi.org/10.1117/12.2536056
27. Gunapala, Sarath; Sir Rafol; David Ting; Alexander Soibel; Arezou Khoshakhlagh; Sam Keo; Brian Pepper; Anita Fisher; Edward Luong; Cory Hill; Kwong-Kit Choi; Arvind D'Souza; Christopher Masterjohn,T2SL LWIR Digital Focal Plane Arrays for Earth Remote Sensing Applications, 2019 IEEE Research and Applications of Photonics in Defense Conference (RAPID), Miramar Beach, FL, USA, 2019, pp. 1-3. DOI: 10.1109/RAPID.2019.8864258 (Invited)
28. Gunapala, Sarath; Sir Rafol; David TIng; Alexander Soibel; Arezou Khoshakhlagh; Sam Keo; Brian Pepper; Anita Fisher; Cory Hill; Kwong-Kit Choi; Arvind D'Souza; Christopher Masterjohn; Sachidananda R. Babu; Parminder Ghuman. Type-II strained-layer superlattice digital focal plane arrays for earth remote sensing instruments. Proceedings of SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII; 1115110 (2019) https://doi.org/10.1117/12.2527731
29. Jafari M, LJ Guo, M Rais-Zadeh. Application of phase change material in tunable optical filters and shutters Micro-and Nanotechnology Sensors, Systems, and Applications XI 10982, 109820W
30. Jafari, M, LJ Guo, M Rais-Zadeh Selective light modulation in waveguide grating using phase change materials (Conference Presentation). Integrated Optics: Devices, Materials, and Technologies XXIII 10921, 109210L
31. Jafari, M, LJ Guo, M Rais-Zadeh Event: SPIE Smart Structures + Nondestructive Evaluation, 2019, Denver, Colorado, United StatesA reconfigurable color reflector by selective phase change of GeTe in a multilayer structure Advanced Optical Materials 7 (5), 1801214 (2019)
32. Jafari,M, LJ Guo, M Rais-Zadeh, Waveguide Grating Color Reflector Using Germanium Telluride 2019 20th International Conference on Solid-State Sensors, Actuators and ...
33. Karasik, B.S., D.P. Cunnane, J.H. Kawamura, D.J. Hayton, N. Acharya, W. Withanage, X. Xi, Far- and Mid-IR Heterodyne Detectors Based on MgB2, 2019 44th Int. Conf. IR, MM & THz Waves (IRMMW-THz), DOI: 10.1109/IRMMW-THz.2019.8874175
34. Kawamura, J., D. Cunnane, B. Karasik, B. Bumble, D. Hayton, I. Mehdi, G. Chattopadhyay, M. Alonso-delPino, J. Siles, C. Curwen, and B. Williams, Development of THz Superconducting HEB Receiver Systems for Balloons, Aircraft, SmallSats and Future Large Missions, Proc. 31st International Symposium on Space Terahertz Technology (ISSTT), Tempe, AZ, USA, March 2020.
35. Keicher, D., M. Essien, F-G. Fan, N. Verdier, J-B. Renard, J. Simcic, and D. Nikolić, Advanced Aerosol Separator for PM2.5 Chemical Composition and Size Distribution Analysis, 50th International Conference on Environmental Systems ICES-2020-351, 12-16 July 2020, Lisbon, Portugal (2020).
36. Lee, C., M. Alonso-delPino, C. Jung-Kubiak, I. Mehdi, D. González-Ovejero, and G. Chattopadhyay Fabrication Of Devices And Antennas For Millimeter-Wave And Terahertz Systems, Proc. 44th International Conference on Infrared, Millimeter, and THz Waves, Paris, France, September 2019.
37. Lee, Choonsup, D. Gonzalez-Ovejero, M. Alonso-delPino, C. Jung, I. Mehdi, and Goutam Chattopadhyay, Fabrication of Devices and Antenna for Millimeter-Wave Terahertz Systems, 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW) 2019 September 1-6
38. Maiwald, F.s S. Madsunkov, D. Nikolic, J. Simcic, R. Kidd, M. Gonzalez, A. Belousov, B. Bae, M., V. Lopez, B. Kim, Planetary Mass Spectrometry 389Team, Compact QIT-Mass Spectrometers for Lunar and Planetary Applications, Presentation at LPC2W December 02, 2019, Orleans, France; Sondermolequium, I. Physikalisches Institut der Universität zu Köln, Germany, December 05, 2019; Extraordinary Space Seminar December 13, 2019, University of Bern, Switzerland.
39. Maiwald, Frank, Stojan Madzunkov, Murray Darrach, Dan Fry, Patrick McNally, Dragan Nikolic, Jim M. Raines, Jurij Simcic, Sarah Waller, Anton Belousov, Peter Willis, QIT-Mass Spectrometer for Lunar and Planetary Applications, 13th HEMP workshop in September 2019, Myrtle Beach
40. Mehdi, Imran, Christine P. Chen, Jose Siles, Silicon Micro-machined 2 THz Mixer for 3-D Winds, Darren Hayton, Research Conference Day, RPC-150 (RT&D), submitted Sept 25, 2019, Pasadena, CA.
41. Nikolić, D., D. Keicher, F.-G. Fan, Design of an Aerodynamic Lens for PM2.5 Chemical Composition Analysis, Proceedings of the 49th International Conference on Environmental Systems, July 7-11, 2019 Boston Omni Parker House, Boston, MA (ICES-2019-366).
42. Nikolic, D., J. Simcic, and S. Madzunkov, Expected Performance of the QIT-MS Mass Spectrometer in Venus' Atmosphere, 17th Meeting of the Venus Exploration and Analysis Group (VEXAG), November 6-8, 2019 in Boulder, Colorado USA, LPI Contribution No. 2193, id.8024 (2019).
43. Pepper, B. J., K. Y. Yee, A. Soibel, A. M. Fisher, S. A. Keo, A. Khoshakhlagh, S. D. Gunapala GaSb grass as a novel antireflective surface for infrared detectors, , Infrared Technology and Applications XLV 11002, 110020X, May 2019, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/11002/110020X/GaSb-grass-as-a-novel-antireflective-surface-for-infrared-detectors/10.1117/12.2521095.short?SSO=1

44. Pradhan, Omkar, Ken Cooper, Leslie Tampari, Brian Drouin, Raquel Monje, Richard Roy, Jose Siles and Corey Cochrane,Submillimeter Wave Differential Absorption Radar For Water Vapor Sounding In The Martian Atmosphere, Int, Symp, on Space THZ Technology, 2020

45. Rahiminejad, S., C. Jung-Kubiak, M. Rais-Zadeh, and G. Chattopadhyay, Contactless rotating MEMS waveguide switch for water detection at 557 GHz, Proc. 31st International Symposium on Space Terahertz Technology (ISSTT), Tempe, AZ, USA, March 2020.

46. Robert Wright; Miguel Nunes; Paul Lucey; Luke Flynn; Sarath Gunapala; David Ting; Sir Rafol; Alexander Soibel; Chiara Ferrari-Wong; Andrea Gabrieli; Prasad Thenabail .HYTI: thermal hyperspectral imaging from a CubeSat platform, SPIE Proceedings 11131, CubeSats and SmallSats for Remote Sensing III; 111310G (2019) https://doi.org/10.1117/12.2530821

47. Schowalter, S. J., B. Bae, I. Cisneros, E. Diaz, M. P. Gonzalez, M. L. Homer, R. D. Kidd, B. Moore, D. Nikolić, A. Oyake, R. Purcell, K. Reichenbach, R. Schaefer, J. Simcic, S. Madzunkov, and M. Darrach, The Technology Demonstration of the Spacecraft Atmosphere Monitor, Proceedings of the 49th International Conference on Environmental Systems, July 7-11, 2019 Boston Omni Parker House, Boston, MA (ICES-2019-321)

48. Siles, J. V., J. H. Kawamura, C. Lee, G. Chattopadhyay, R. H. Lin, M. Alonso-del-Pino and M. Choukroun, Ultra-Broadband Submillimeter-Wave Schottky Array Receivers for High Spectral Resolution Spectroscopy of Moons and Comets, IEEE International Microwave and RF Conference (IMaRC), Mumbai, India, December 2019.

49. Siles, Jose V., Jonathan Kawamura, Robert Lin, Choonsup Lee, Alain Maestrini, Darren Hayton, Ken Cooper, Maria Alonso del Pino and Imran Mehdi Compact Multi-Pixel Frequency Multiplied Local Oscillator Sources for Wideband Array Receivers in the 200-600 GHz & 1.4-2.7 THz Ranges, , Int, Symp, on Space THZ Technology, 2020

50. Siles, Jose V., Jorge Pineda, Jonathan Kawamura, Christopher Groppi, Pietro Bernasconi, Joshua Gundersen and Paul Goldsmith ,ASTHROS - Astrophysics Stratospheric Telescope for High-Spectral Resolution Observations at Submillimeter-waves: Mission Overview and Development Status, Int, Symp, on Space THZ Technology, 2020

51. Simcic, J., J. C. Lee, S. Madzunkov, D. Nikolić, and A. Belousov, Piezo-electric inlet system for atmospheric descent probe, Proceedings of the Workshop on In Situ Exploration of the Ice Giants, 25-27 February Marseille, France (2019).

52. Simcic, J., J.C. Lee, S. Madzunkov, D. Nikolic, A. Belousov, Piezo-Electric Inlet System for Atmospheric Descent Probe, 16th International Planetary Probe Workshop & Short Course titled • Ice Giants: Exciting Targets for Solar System Entry Probes Exploration • 6–7 July 2019 Oxford University

53. Sterczewski, Lukasz A., Mahmood Bagheri, Clifford Frez, Chadwick L. Canedy, Igor Vurgaftman, Mijin Kim, Chul Soo Kim, Charles D. Merritt, William W. Bewley, and Jerry R. Meyer, Interband Cascade Laser Frequency Combs (invited), 6th International WORKshop on Infrared Technologies, Princeton, NJ, USA, October 29-30 (2019).

54. Sterczewski, Lukasz A., Mahmood Bagheri, Clifford Frez, Igor Vurgaftman, Jerry R. Meyer, Injection locking of interband cascade laser frequency combs, Infrared Terahertz Quantum Workshop, Ojai, CA, USA, September 15-20 (2019).

55. Ting, David Z.; Alexander Soibel; Arezou Khoshakhlagh; Sam A. Keo; Sir B. Rafol; Edward M. Luong; Anita M. Fisher; Brian J. Pepper; Cory J. Hill; Sarath D. Gunapala, InAs/InAsSb Type-II Strained Layer Superlattice Barrier Infrared Detectors. 2019 IEEE Photonics Conference (IPC), San Antonio, TX, USA, 2019, pp. 1-2. DOI: 10.1109/IPCon.2019.8908487

56. Verma V. B. et al. Towards single-photon spectroscopy in the mid-infrared using superconducting nanowire single-photon detectors. Proc. SPIE 10978, Advanced Photon Counting Techniques XIII, (2019)

57. Whitton, Cassandra, Christopher Groppi, Philip Mauskopf, Jose Siles and Adrian Tang Development of a Dual-Band Metamaterial Lens for Cubesat Water Observation, , Int, Symp, on Space THZ Technology, 2020

58. Wright, Robert; Miguel Nunes; Paul Lucey; Luke Flynn; Thomas George; Sarath Gunapala; David Ting; Sir Rafol; Alexander Soibel; Chiara Ferrari-Wong; Abigail Flom; John Mecikalski; Prasad Thenkabail; the HyTI Team. HyTI: Thermal Hyperspectral Imaging from A Cubesat Platform, IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 2019, pp. 4982-4985. DOI: 10.1109/IGARSS.2019.8899887

59. Yoo, C., M. Huang, J. Kawamura, K. W. West, B.S. Karasik, L. N. Pfeiffer, and M. S. Sherwin, Demonstration of a TACIT Heterodyne Detector at 2.5 THz, Proc. 30th Int. Symp. Spc. THz Technol., April 15-17, 2019, Gothenburg, Sweden, p.191.

60. Yoo, C., M. Huang, J. Kawamura, K. W. West, B.S. Karasik, L.N. Pfeiffer, and M.S. Sherwin, Demonstration of a Frequency-Agile Quantum Well Based THz Heterodyne Detector, 2019 44th Int. Conf. IR, MM & THz Waves (IRMMW-THz), DOI: 10.1109/IRMMW-THz.2019.8874259

61. Yurduseven, O., C. Lee, N. Chahat, D. González-Ovejero, M. Ettorre, R. Sauleau, and G. Chattopadhyay, Design of a Quasi-Optical Si/GaAs W-Band Beam-Forming Metasurface Antenna, Proc. IEEE International Symposium on Antennas and Propagation, Atlanta, GA, USA, July 2019.

62. Yurduseven, O., D. González-Ovejero, M. Ettorre, R. Sauleau,V. Fusco, G. Chattopadhyay, and N. Chahat Towards a Si/GaAs Based Flat-Panel Quasi-Optical Metasurface Antenna with Switchable Beam Characteristics, Proc. 13th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, April 2020.

Book Contributions

None for 2019

New Technology Reports

1. Briggs Ryan M., (2019) Ultraviolet lasers based on upconversion in orientation-patterned crystals, NTR 51386.
2. Briggs, Ryan M., Clifford F. Frez, and Mathieu Fradet, (2019) Tapered-grating single-mode lasers, NTR 51405.
3. Coleman, M and Christensen, L. E., (2019) An apparatus to sample without a membrane for in-situ underwater gas analysis using capillary absorption spectrometry, NTR# 51275.
4. Cunnane, D., B. Karasik, S. Cybert, and A. Cortez, (2019) Josephson Mixer Based on Focused Ion Beam Direct Writing of YBCO Josephson Junctions, NTR #51503,
5. Ledezma, Luis M., Hernandez, Ryan M. Briggs, Alireza Marandi, and Yinglun Xu, (2019) Thin-film optical parametric oscillator, NTR 51163.
6. Mathieu, Fradet, M. Briggs, Linda Y. Del Castillo, and Rais-Zadeh, (2019) Infrared/visible optical flow sensor for multi-phase mixtures, NTR 51456.

Patents

1. Chattopadhyay, G., C. D. Jung-Kubiak, T. J. Reck, D. Gonzalez_Ovejero, M. Alonso-delPino, Low-profile and high-gain modulated metasurface antennas from gigahertz to terahertz range frequencies, US 10,418,721 B2, September 17, 2019.
2. Coleman, M and Christensen, L. E. An Apparatus to Sample Without a Membrane for In-Situ Underwater Gas Analysis Using Capillary Absorption Spectrometry CIT File No.: CIT-8324-P. Filed: 7/31/2019. US patent pending.US patent pending.
3. Khoshakhlagh, Arezou, David Z. Ting and Sarath D. Gunapala, "P-compensate and P-doped superlattice infrared detectors" Patent Number: 9,831,372. Issued: 11/28/2017.
4. Siles, Jose V., and others. On-Chip Diplexed Multi-Band Submillimeter-Wave/Terahertz Sources", CIT Preliminaty Patent File No.: CIT-8386-P, Filed: 11/7/2019. US patent pending.
5. Ting, David Z., Alexander Soibel, Arezou Khoshakhlagh, Sarath Gunapala "Unipolar barrier dual-band infrared detectors", Patent Number: 9.799,785 Issued: 11/24 /2017.

Awards and Recognition by External Organizations

1. Sarath Gunapala received the MSS Levinstein Award from the Military Sensing Symposia (MSS) for "outstanding technical and management contributions in the development of infrared focal plane arrays for the military sensing community and national defense under the Vital Infrared Sensor Technology Acceleration (VISTA) program.".
2. Fernanda Mora was invited to contribute a manuscript to the "Emerging Investigator Series in Analytical Methods" that aims to highlight research being conducted by early-career scientists in the field of analytical chemistry.
3. Konstantin Zamuruyev received an Award for Best Doctoral Dissertation from the College of Engineering at the University of California, Davis. The award recognized his research on "Development of a Portable System for Analysis of Exhaled Breath Condensate" with a hand-held CE-ESI device.

MDL EQUIPMENT COMPLEMENT

Material Deposition

- Thermal Evaporators (5)
- Electron-Beam Evaporators (7)
- Angstrom Engineering Indium-Metal Evaporator
- AJA Load Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- PlasmaTherm 790 Plasma Enhanced Chemical Vapor Deposition (PECVD) for Dielectrics with Cortex Software Upgrade
- Oxford Plasmalab System 100 Advanced Inductively Coupled Plasma (ICP) 380 High-Density Plasma Enhanced Chemical Vapor Deposition (HD PECVD) System for Low-Temperature Dielectric Growths 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
- Tystar (150-mm/6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 3 Tubes for
  - o Low-Stress Silicon Nitride
  - o Atmospheric Wet/Dry Oxidation
  - o Oxy-Nitride growths
- Carbon Nanotube (CNT) Growth Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  - o Veeco GEN200 (200-mm/8-inch) Si MBE for UV CCD Delta Doping (Silicon) with computer upgrades
  - o Veeco Epi GEN III MBE (III-V Antimonide Materials)
  - o 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:
  - o Karl Suss MJB3
  - o Karl Suss MJB3 with backside IR
  - o Suss MA-6 (UV300) with MO Exposure Optics upgrade
  - o Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
  - o Suss Gamma 4-Module Cluster System
  - o Site Services Spin Developer System
  - o 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)
- Unaxis Shuttleline Load-Locked Fluorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm APEX SLR Fluorine-based ICP RIE with Laser End Point Detector with SW upgrade
- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 Etcher
- Oxford PlasmaPro 100 Cobra Load-Locked Cryo Etching / Atomic Layer Etching / Bosch Etching System, primarily for Black Silicon.

Chlorine-based Plasma Etching Systems

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

Wet Etching & Sample Preparation

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (7)
- Rinser/Dryers for Wafers including Semitool 870S Dual Spin Rinser Dryer
- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Jelight UVO-Cleaners (2)
- Novascan UV8 Ultraviolet Light Ozone Cleaner
- Tousimis 915B Critical Point Dryer
- Solaris 150 Rapid Thermal Processor
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher
- Precitech Nanonform 250 Ultra Diamond Point Turning System
- SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool with upgrade
- SurfX Atomflo 500 Argon Atmospheric Plasma Surface Activation System for wafer bonding
- 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

Appendices, cont.

Characterization

- Profilometers (2) (Dektak 8 and Alphastep 500)
- Frontier Semiconductor FSM 128-NT (200-mm/8-inch) Film Stress and Wafer Bow Mapping System
- LEI 1510 Contactless Sheet Resistance Tool
- FISBA µPhase 2 HR Compact Optical Interferometer
- Horiba UVSEL 2 (190–2100 nm) Ellipsometer
- Filmetrics F20-UV (190-1100 nm) Thin Film Spectrometer Measurement System
- Filmetrics F40-UVX (190-1700 nm) Thin Film Spectrometer Measurement System with Microscope
- Bruker Dimension 5000 Atomic Force Microscope (AFM)
- Park Systems Inc. NX20 Atomic Force Microscope (AFM)
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- Surfscan 6200 Surface Analysis System Wafer Particle Monitor with upgraded Software
- JEOL JSM-6700 Field Emission SEM with EDX
- Hitachi Regulus 8230 UHR Cold Field Emission SEM with Aztec Energy Dispersive X-ray Microanalysis System and Critical Dimension Measurement capabilities
- Nanospec 2000 Optical Profilometer
- Nikon and Zeiss Inspection Microscopes with Image Capture (3)
- Keyence VHX-5000 Digital Microscope including low power lens
- McBain BT-IR Z-Scope IR Microscope Workstation
- Olympus LEXT 3D Confocal Microscope
- Mitaka NH-5Ns 3D Profiler
- Electrical Probe Stations (4) with Parameter Analyzers (2)
- RPM2035 Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectrometers (3) including Bruker Optics Vertex 80 FTIR
- PANalytical X'Pert Pro MRD with DHS High Temperature Stage X-ray Diffraction System
- Surface Science SSX501 XPS with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- Nanometrics ECV Pro Profiler
- VEECO / WYKO NT 9300 Surface Profiler (including 50X optics)
- Zygo ZeMapper non-contact 3D Profile
- Thermo Scientific LCQ Fleet CE / MS (Capillary Electrophoresis / Mass Spectrometer) System
- Lakeshore Cryotronics Model CPX 1.7 Kelvin Cryo Probe Station

MDL

The research described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Visit us at **microdevices.jpl.nasa.gov**

About the back cover: Exoplanet discovery and characterization are a key focus of NASA to understand how Earth and our solar system fit in the universe. This image is an artist's concept of a gas giant exoplanet orbiting its star. MDL is contributing advanced devices and customized space flight packaging for missions with exoplanet capabilities.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.jpl.nasa.gov

www.microdevices.jpl.nasa.gov

CL#20-2833
JPL 400-1728 07/20