National Aeronautics and Space Administration

REACHING FOR NEW HEIGHTS TO REVEAL THE UNKNOWN.

Jet Propulsion Laboratory
California Institute of Technology

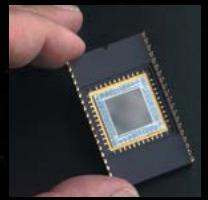
MICRODEVICES LABORATORY

2022 | ANNUAL REPORT


Discovery // STS-48


1991

NASA's Upper Atmosphere Research Satellite (UARS) with Microwave Limb Sounder (MLS)with MDL-fabricated diode receivers for monitoring of ozone chemistry.


Nike-Orion


1996

Nike-Orion Sounding Rocket and the High Altitude Ozone Measuring and Educational Rocket (HOMER) instrument suite with MDL-fabricated delta-doped detector.


Ariane 5

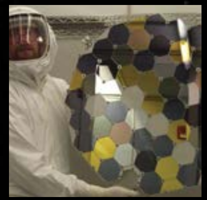

2000

Space Technology Research Vehicle (STRV-1D) with MDL-fabricated four-band Quantum Well Infrared Photodetector (QWIP) focal plane array.

Earth Observing 1 (EO-1): Hyperion high-resolution hyperspectral Imager with 2 MDL e-beam fabricated gratings.

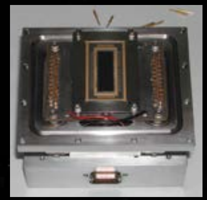

Delta II



Delta 7326-9.5


2001

Genesis mission: MDL coated and qualified over 25% of the solar wind collector arrays.


Black Brant IX


2003-2008

Black Brant IX Sounding Rocket with an MDL processed delta-doped detector in the Long-Slit Imaging Dual Order Spectrograph (LIDOS) that was used on three missions.

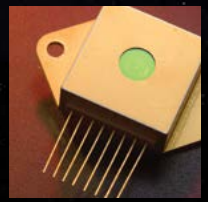

Ariane 5


2009

Planck Observatory, High Frequency Instrument (HFI) with MDL-fabricated spider-web and polarization-sensitive bolometers.

Herschel Space Observatory (HSO): Spectral and Photometric Imaging Receiver (SPIRE) with MDL-fabricated enabling detectors.

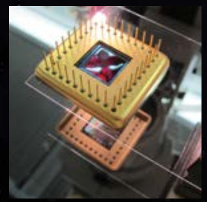
HSO: Heterodyne Instrument for the Far Infrared (HIFI) with MDL-fabricated enabling detectors.


Atlas V


2011

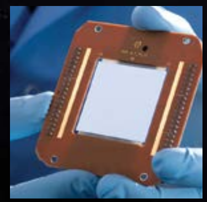
Mars Science Laboratory (MSL): Curiosity Rover, Tunable Laser Spectrometer-Sample Analysis at Mars (TLS-SAM) instrument suite with MDL-fabricated tunable diode lasers.

Over 30 years of innovative deliveries for NASA.


Terrier-Black


2012

Magnetosphere Ionosphere Coupling in the Alfven Resonator (MICA) sounding rocket and MDL-processed low voltage delta-doped CCD array.


Black Brant IX


2018

NASA/University of Colorado Boulder Sounding Rocket Mission 36.333 UG, Colorado High-resolution Echelle Stellar Spectrograph (CHESS-4) with MDL-processed back-illuminated delta-doped CCDs.


SpaceX Falcon 9 CRS-15

International Space Station (ISS): ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) with MDL black silicon calibration targets.


Ariane 5 G


2004

Rosetta Orbiter: Microwave Instrument for the Rosetta Orbiter (MIRO) with a 557-GHz radiometer with subharmonic planar diode mixers and multipliers fabricated at MDL.

Aura: The Earth Observing System (EOS) Microwave Limb Sounder (MLS) with MDL-fabricated 190/240/640-GHz and 2.5-THz mixers launched in 2004 on a Delta II rocket.


Atlas V


2005

Mars Reconnaissance Orbiter (MRO), Mars Climate Sounder (MCS) instrument with MDL-fabricated uncooled IR thermopile detectors.

Mars Reconnaissance Orbiter (MRO): Compact Reconnaissance Imaging Spectrometer (CRISM) with 2 MDL-fabricated convex dual-blaze gratings.


PSLV-XL C11


2008

Chandrayaan-1, an Indian Space Research Organization (ISRO) mission including the Moon Mineralogy Mapper (M3) instrument with MDL e-beam fabricated shaped-groove gratings.


Minotaur I


2009

TacSat-3 spacecraft: Advanced Responsive Tactically Effective Military Imaging Spectrometer (ARTEMIS), with MDL-fabricated shaped-groove grating and e-beam lithograph slit.


Atlas V


2009

Lunar Reconnaissance Orbiter (LRO): Diviner Lunar Radiometer Experiment Instrument with MDL-fabricated thermopile detectors.

SpaceX Falcon 9 CRS-18

2019

ISS: Spacecraft Atmosphere Monitor (SAM), with MDL-fabricated components for the gas chromatograph–mass spectrometer (GCMS).

SpaceX Falcon 9 CRS-17

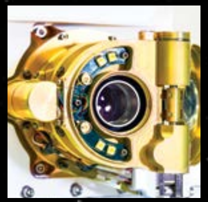
2019

International Space Station (ISS): Orbiting Carbon Observatory 3 (OCO3) with MDL-fabricated slits and black silicon stray light control element.

Atlas V 541


2020

Mars 2020, Perseverance Rover: Planetary Instrument for X-Ray Lithochemistry (PIXL) with MDL-fabricated spot-array generator gratings.

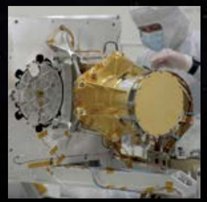


Mars 2020, Perseverance Rover: Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument, with MDL-fabricated gratings.

Ariane 5


2021

James Webb Space Telescope (JWST), NIRCam Coronagraph with MDL e-Beam-fabricated occulting masks.

Space X Falcon 9


2022

ISS, Earth Surface Mineral Dust Source Investigation (EMIT), with MDL-fabricated grating, slit, and stray light control devices.

MDL has a strong track record

MDL innovates, invents, delivers, and changes the way we look at the universe.

Jet Propulsion Laboratory Microdevices Laboratory
2022 | ANNUAL REPORT

Reaching for New Heights to Reveal the Unknown

Since JPL's Microdevices Lab (MDL) opened, its facilities and expert staff have supported and enabled increasingly ambitious NASA missions. The airborne instruments developed in the 1990s paved the way for balloon-borne demonstrations, satellite-based instruments, and technologies that have gone to the Moon and Mars.

The MDL-enabled instruments on these missions have revealed new and sometimes paradigm-shifting information about our planet and our solar system.

As NASA outlines its next goals in its Decadal Surveys, MDL will keep the pace by remaining at the forefront of microdevice design and fabrication; examples of these innovations are outlined in this report. These instruments will help us learn about unexplored corners of our solar system and beyond, and MDL will make them possible.

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

New director appointed for NASA's Jet Propulsion Laboratory

THIS DISTINGUISHED GEOCHEMIST AND SPACE SCIENTIST BRINGS MORE THAN 20 YEARS OF LEADERSHIP EXPERIENCE IN ACADEMIC AND GOVERNMENT SERVICE TO JPL.

Dr. Leshin is an internationally recognized scientist whose career has spanned academia and senior positions at NASA, and included two White House appointments. She has been lauded for her barrier-breaking leadership in the space industry and in academia as well as for her accomplishments as a distinguished geochemist and space scientist.

> I am both thrilled and humbled to be appointed the director of JPL. In many ways, this feels like a homecoming. Some of the most impactful experiences of my career have taken place on the Caltech campus and at JPL.

TO BEGIN, JPL LEADERSHIP AND I WANT TO EXPRESS OUR PROFOUND THANKS TO THE EXTRAORDINARY GROUP OF SCIENTISTS, TECHNOLOGISTS, AND STAFF WHO MAKE MDL THE SUCCESS IT IS TODAY.

Their efforts have made this another extraordinary year for MDL. We have continued our track record and focus on developing enabling devices for state-of-the-art NASA missions.

Thanks to the MDL team, recent MDL devices are on the International Space Station enabling new Earth science, studying the surface of Mars on the Perseverance rover, and helping observe the heart of universe on the James Webb Space Telescope, among many other achievements. The back cover and first two pages of this Annual Report highlight a broad set of launches, missions, and instruments that include MDL devices.

Building on this legacy and looking forward, MDL is strongly supporting elements of the current Decadal Surveys for Planetary Science and Astrobiology, Astronomy and Astrophysics, and Earth Science and Applications. In parallel, an exciting set of next-generation exploratory device investigations are being undertaken by postdoctoral researchers and MDL scientists to lay the groundwork for new devices with infusion potential for later in this decade and beyond.

I hope you find many topics of interest in this Annual Report. Please reach out to us if you see opportunities for collaboration as we look to support new advances in science, exploration, and discovery for NASA.

ROBERT GREEN
Director, Microdevices Laboratory

THIS YEAR MARKS MY 33RD YEAR AT JPL AND MY 15TH AS DEPUTY DIRECTOR OF MDL. EVEN AFTER MORE THAN THREE DECADES, I STILL LOOK FORWARD TO COMING TO WORK EVERY DAY.

Why? Because JPL empowers people to explore, the work we do, and JPL engages everyone, both inside and outside the Lab, with fascinating new information about the universe and life. It is full of amazing, talented people who are driven by the desire to accomplish great things while having fun and sharing their discoveries with the world, and I am excited to see this culture continue under JPL's new director, Laurie Leshin.

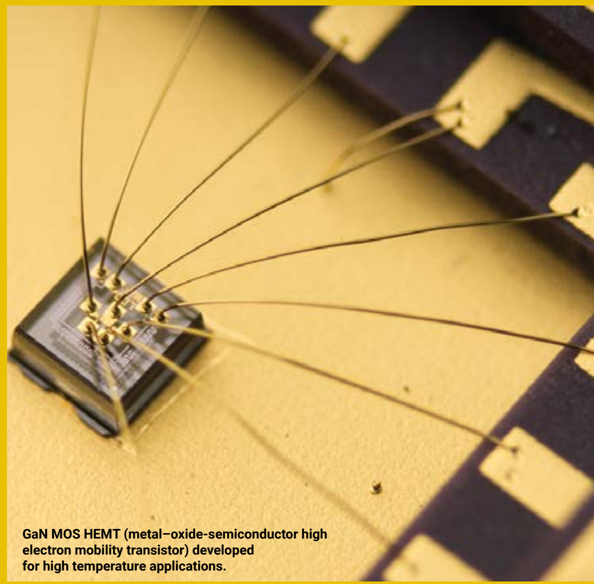
At JPL, we derive meaning from our work knowing that we are doing more than just a job; rather, we are helping advance human knowledge and improving lives. Many institutions aspire to change the world, but JPL is particularly capable of realizing that aspiration because it is endowed with the talent, resources, and perseverance to truly shift paradigms.

This uniqueness is especially apparent for me when I put together the MDL annual report and see the incredible progress made during the previous year. This year is no exception. I never cease to be impressed by the MDL teams' accomplishments, and I am fortunate to work with them. I wholeheartedly believe that JPL and MDL are among the best places in the world to work, and serving as the Deputy Director of MDL continues to be an incredible honor.

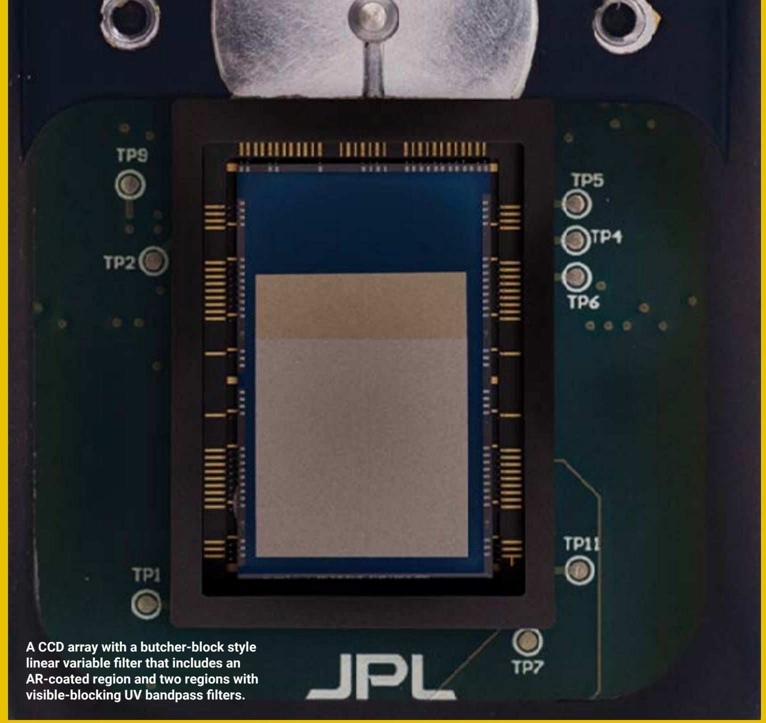
SIAMAK FOROUHAR
Deputy Director, Microdevices Laboratory

Shaped pupil spectroscopy mode mask for the Roman Telescope.

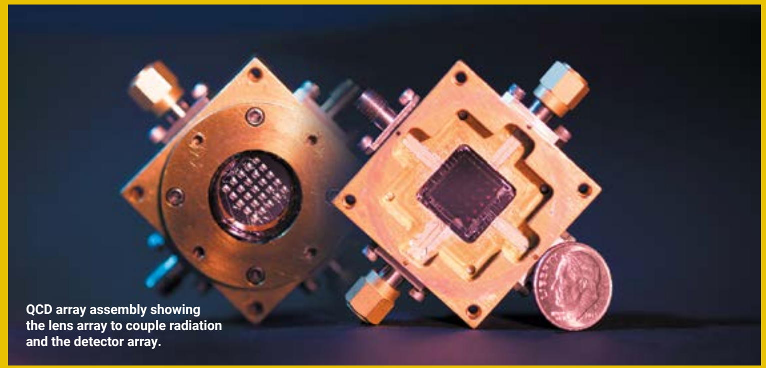
MDL E-beam fabricated concave flight grating for MISE.



GaN MOS HEMT (metal–oxide-semiconductor high electron mobility transistor) developed for high temperature applications.



A CCD array with a butcher-block style linear variable filter that includes an AR-coated region and two regions with visible-blocking UV bandpass filters.



QCD array assembly showing the lens array to couple radiation and the detector array.

Vision

MDL's vision is to pioneer innovative and unique research and developments in micro-, nano-, and other novel technologies, advance world-class capabilities in the design, fabrication, and characterization of advanced components and sensors, and enable next-generation observation capabilities, instruments, and missions for NASA and our nation.

Charter

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

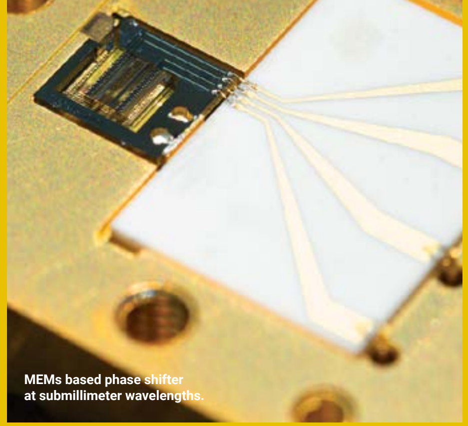
Approach

MDL uses the latest science and technology to invent and deliver novel microdevices and capabilities that enable new missions of discovery and exploration for NASA.

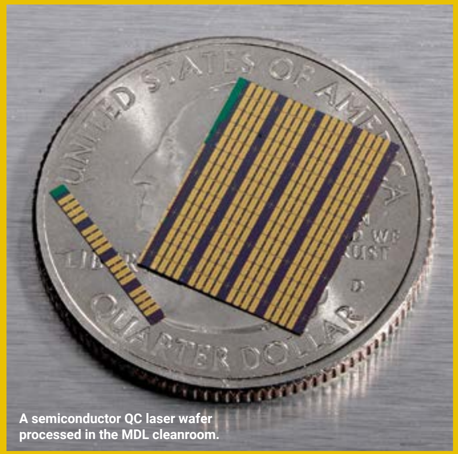
MDL works to attract an exceptional and diverse group of scientists, technologists, and staff to assure it fulfills its vision and charter, now and in the future.

In concert with the advent of "new space," MDL works to accelerate the infusion of new microdevices and related technologies into NASA missions while maintaining the rigorous quality assurance of devices deployed for space missions.

MDL

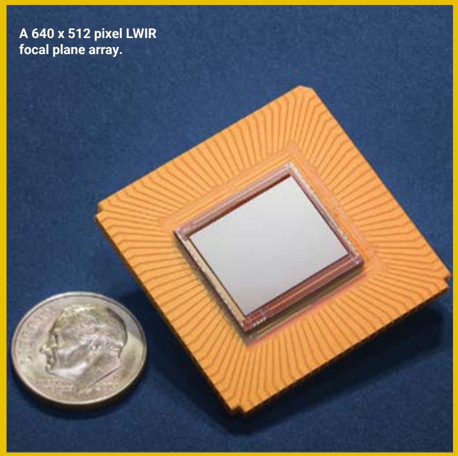


MEMs based phase shifter at submillimeter wavelengths.



A semiconductor QC laser wafer processed in the MDL cleanroom.

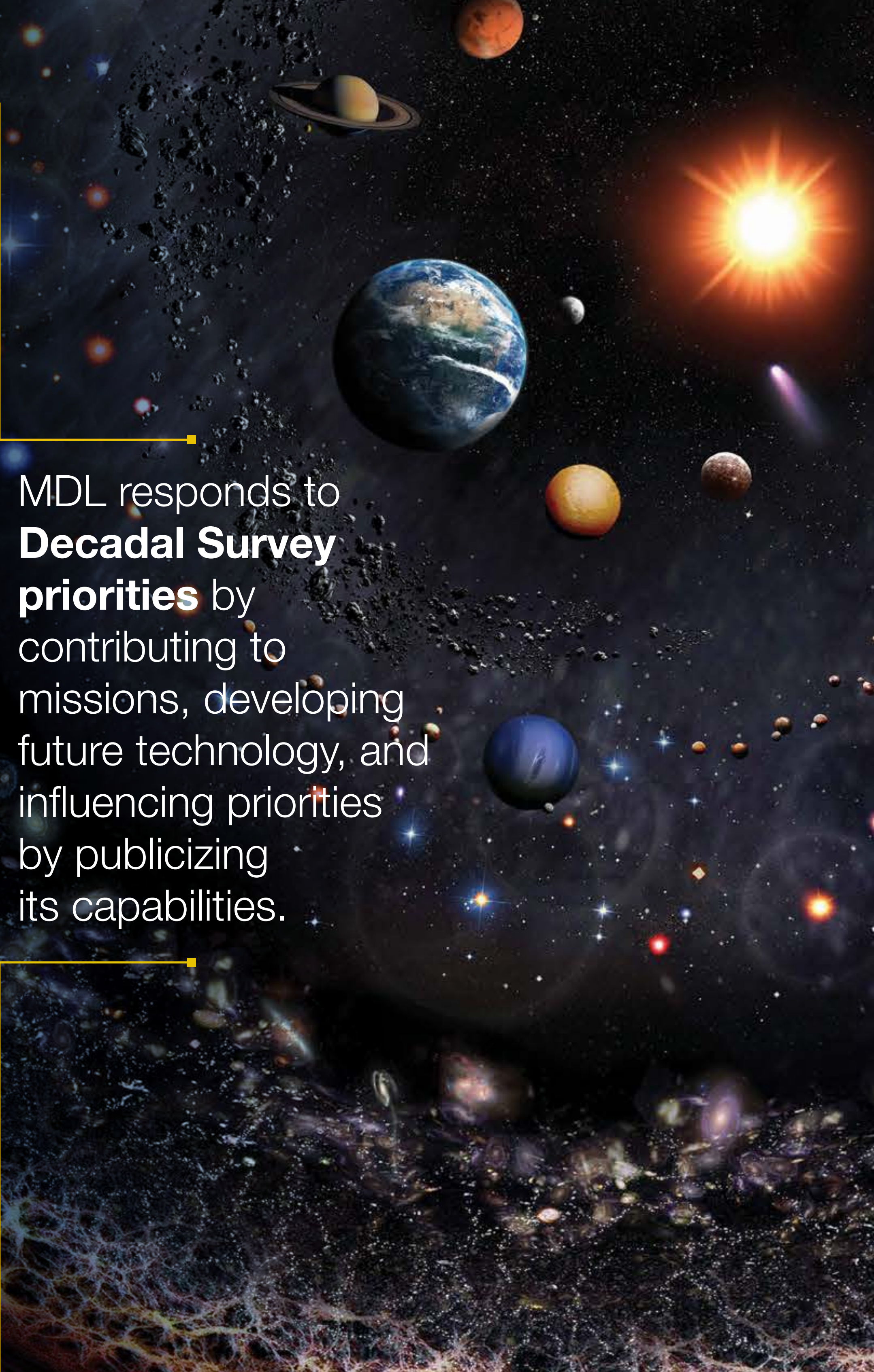
VIPR's RF source 170 GHz Schottky diode frequency-doubler.



A 640 x 512 pixel LWIR focal plane array.

Contents

NASA's science-driven Decadal Surveys overcome inconvenient truths* by focusing the science and technology communities.



MDL responds to **Decadal Survey priorities** by contributing to missions, developing future technology, and influencing priorities by publicizing its capabilities.

***Inconvenient Truths**

1. Technology development for ambitious space science objectives can take a decade or longer to innovate and prepare for the rigors of space flight.
2. The science objectives must be identified decades in advance.
3. It all needs sustained funding, long-term outlook, and patience.

To ensure clear priorities in its science areas, define its goals and focus its funding, NASA has requested the National Academies of Sciences, Engineering, and Medicine to prepare Decadal Surveys in many areas, including space science, Earth science, and astronomy and astrophysics.

Each survey is a major exercise, in some cases requiring almost two years to prepare and write so that each survey is done on an offset schedule.

The National Research Council (NRC), the operating arm of the National Academies of Sciences, gathers opinions from the relevant scientific community, focused by panels on specific topics and by input from numerous white papers to formulate these Decadal Survey reports.

The result is a collection of the most significant scientific questions and a prioritized set of actions, including missions, to address them. Unsurprisingly, if a major flagship mission is recommended, then many years may elapse before its final launch and operation.

The Decadal Surveys are NASA's principal guidance on scientific and budgetary priorities.

Additionally, as a mission is being developed in response to a recommendation in one area, other areas may see the value of using similar assets to further their scientific priorities and support them in their own Decadal Surveys.

The Decadal Surveys not only prioritize the most significant scientific questions and how they should be addressed but also make recommendations to NASA and other government bodies, like the NSF or NOAA, on an appropriate budget for programs and program augmentation. NASA's budget formulation is based on its estimate of its total likely funding, but because the prioritization and resource allocation come from an independent source, it has a much greater impact on Congress than would an internally generated estimate.

Pages 10–15 provide examples of MDL contributions to current Decadal Surveys.

MDL aligns with NASA's Decadal Surveys

Astronomy & Astrophysics

The Astronomy and Astrophysics Decadal Surveys have guided six decades of innovation in space science.

The National Research Council has produced Astronomy and Astrophysics Decadal Surveys since 1964. The resulting six decades of recommendations led to the completion of NASA's Great Observatories — space telescopes launched between 1990 and 2021, including the Hubble Space Telescope and the recently launched James Webb Space Telescope, covering different ranges of the electromagnetic spectrum. A well-deserved congratulatory comment in Astro2020 (a colloquial name for this Decadal Survey) noted that investments in astronomy research over the preceding ten years resulted in the award of six Nobel Prizes in physics, including for discoveries related to dark energy, black holes, and exoplanets.

Astro2020 (2020–2030) prioritizes the key science questions for this decade and outlines the programs necessary to answer them. For space-based instruments, the survey recommends a new NASA process of science and technology maturation for a new set of large observatories. The top priority has been given to a large 6-meter infrared (IR)/optical/ultraviolet observatory directed at the search for biosignatures from habitable-zone exoplanets and for astrophysics in general. Its implementation could start by the end of the 2020 decade if the technology maturation is successful. Additionally, the survey gives high priority to building both far-IR and X-ray large-scale observatories starting in the second half of the decade.

The report also recommends a new line of medium-scale probe missions, with the first two priorities being a far-IR mission and an X-ray mission to complement the European Space Agency's Athena.

These priorities, among several others, provide broad opportunities for MDL, particularly for the detectors and electron-beam metasurfaces that have been continuously developed and improved at the lab. A few examples are provided in the following pages to illustrate how MDL is positioned to make significant contributions to many of these NASA priorities.

CGI

The Nancy Grace Roman Space Telescope, the top recommendation of the 2010 Decadal Survey, was delayed to a 2027 launch date due to the cost overruns of the James Webb Space Telescope. The 2020 Astronomy and Astrophysics Decadal Survey stated that its future plan was based on the assumption that the operations and science of the previous surveys' major missions would be fully supported. This assumption put the Roman Space Telescope, capable of making observations in the optical and infrared regions of the electromagnetic spectrum, at the top of the current priority list.

JPL is developing a coronagraph instrument (CGI) for the Roman Space Telescope that relies on critical MDL technologies. The CGI blocks the light of a star, allowing its planets to be much more sensitively and clearly imaged. Instead of using a disc to physically block the light, the instrument uses MDL's optical interference technology, which relies on electron-beam lithography fabrication techniques. The CGI was included in the original mission proposal in 2013 and demonstrated in a flight operation in a test bed in 2019.

The successful progress of the instrument was made possible by foresight and prescient investment in facilities at JPL and MDL.

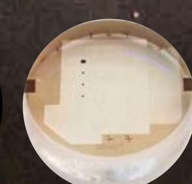
The CGI will be the first advanced coronagraph instrument to be flown, and it is 1,000 times more capable than previous coronagraphs.

SPC black silicon mask

Mask profile measured using atomic force microscopy

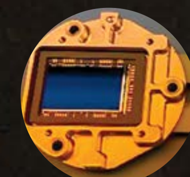
Shaped Pupil Coronagraph (SPC)

HLC Lyot stop

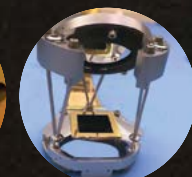


Focal plane mask

Hybrid Lyot Coronagraph (HLC)

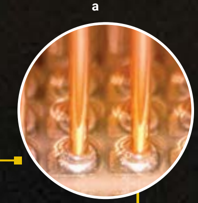


EDU chip

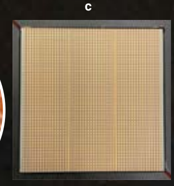


EDU sensor/mirror sub-assembly

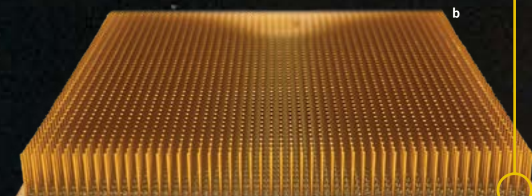
Engineering development unit (EDU)



a



c



b

Deformable Mirror

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

MKIDs

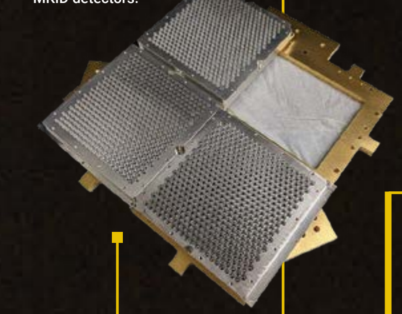
Pushing the frontiers of knowledge of the formation and evolution of galaxies and the structure of the universe requires advanced far-infrared (IR) detector technology. Much of our early universe, as well as the center of our own Milky Way galaxy, is shrouded by clouds of dust that obscure our visible-wavelength view. But dust is transparent in far-IR and submillimeter wavelengths, allowing observers to see through vast dust clouds. This dust also absorbs high-energy light from the hidden stars within, which it then thermally emits in the far-IR. These properties result in hidden stellar nurseries being bright in the far-IR even if they are dark in the visible/ultraviolet. Because our universe is expanding, the light of receding galaxies is redshifted so that optical wavelengths are stretched further into the far-IR.

One of the most promising far-IR detector technologies is microwave kinetic inductance detectors (MKIDs), which have been under development by Caltech and JPL since the early 2000s. MKIDs are superconducting resonators that respond to light with a change in surface impedance and resonant frequency as Cooper pairs break up. MKIDs have a fundamental advantage in sensitivity over conventional technologies because the superconducting band gap energy is 2–3 orders of magnitude smaller. MKIDs also have a low noise equivalent power, and they can be frequency multiplexed by altering their physical structure to slightly different resonant frequencies. These advantages promise the high mapping speeds needed in sub/millimeter cameras.

MDL's significant advances in materials, fabrication processes, and designs for MKIDs over the last 2 decades are enabling background-limited wide-field spectral surveys for the first time in the far-IR (25 µm – 350 µm).

MKIDs are currently baselined for a joint JPL/Goddard mission concept for a high-priority far-IR observatory recommended in the Astro2020 Decadal Survey.

3840 feedhorn coupled MKID detectors.



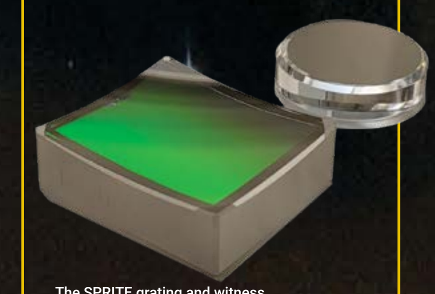
The SPARCS NUV detector's peak sensitivity is at 280 nm, and the FUV peaks at ~160 nm.

UV mirror

The Decadal Survey gave the highest priority to a future flagship mission with capabilities from infrared to optical to ultraviolet (UV) to support all three of its main themes; this mission will have objectives ranging from astrophysics to exoplanet detection and investigation. It will require advances in mirror coating performance, stability, and uniformity.

Work at MDL is supporting the development of new UV mirror coating processes in response to these requirements.

Specifically, a NASA Strategic Astrophysics Technology program is being led by a JPL team that will advance the readiness level of meter-class protected aluminum mirror coatings fabricated with atomic layer deposition.



The SPRITE grating and witness sample following deposition of the ALD protective layer at MDL.

UV CCDs

The Star-Planet Activity Research CubeSat (SPARCS), funded by the NASA Astrophysics Research and Analysis (APRA) program, responds to the prioritization of exoplanets in the last two Decadal Surveys. SPARCS is a small space telescope, a 6U CubeSat. The objective of the mission is to look at M-type (red dwarf) stars.

This seemingly unlikely choice of target was made because although M-type stars are much smaller and much less luminous than the Sun, they are abundant, and a planet with an orbit near one could possibly be habitable. However, being near a star exposes a planet to potentially harmful radiation. The objective of the mission is to make highly time-resolved observations to examine ultraviolet (UV) flare emissions from these stars, which are much more active than the Sun. The mission will be a testbed for technology that could be used in later much-larger-scale space telescopes.

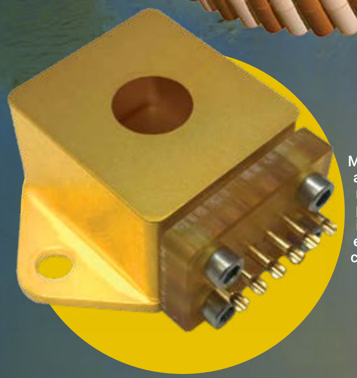
MDL is providing the UV detectors, which are essential for the mission.

At the request of NASA, the NRC established the Solar System Exploration Survey to undertake a study similar to the already established Decadal Surveys for Astronomy and Astrophysics.

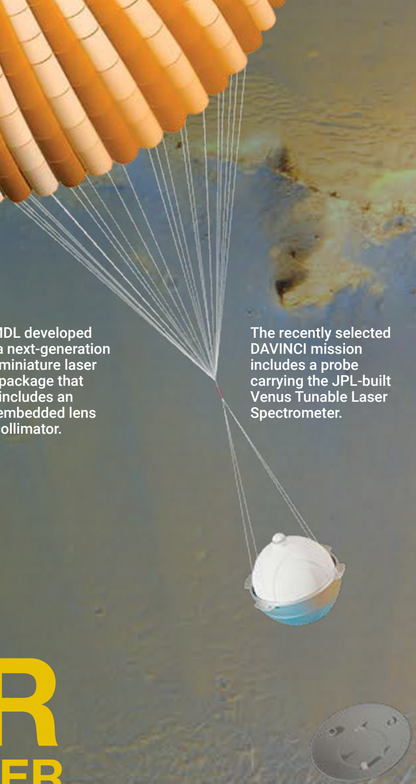
Three Decadal Surveys on Planetary Science have been released to date. The first, "New Frontiers in the Solar System: An Integrated Exploration Strategy," was released in 2002 and covered 2003-2013. It prioritized specific missions of various class sizes but also very strongly endorsed Discovery-class missions, stating, "that adequate resources be provided to sustain an average flight rate of no less than one launch every 18 months." The second survey was released in 2011 for the 2013-2022 period.

The third and current, "Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032," was released in April 2022 for 2023-2032. Its top recommendations are the completion of the Mars Sample Return campaign and a Uranus Orbiter and Probe flagship, followed by an Enceladus Orbilander flagship for detecting life. Other recommendations are outlined in a proposed ambitious "recommended" program and a more cost-conscious "level" program. This strategy recognizes that there are several high-priority flight missions that for various reasons could not be achieved as flagship missions in the stated decades but nevertheless should be addressed. These missions include a medium-class mission to an asteroid.

The Tunable Laser Spectrometer, the Lunar Trailblazer and the Deep Space Optical Communications projects are just three examples of how MDL is already positioned to contribute to NASA's next decade of planetary exploration.



MDL developed a next-generation miniature laser package that includes an embedded lens collimator.



The recently selected DAVINCI mission includes a probe carrying the JPL-built Venus Tunable Laser Spectrometer.

TUNABLE LASER SPECTROMETER

MDL has a long history of developing infrared tunable semiconductor lasers for a wide variety of space applications. In partnership with industry, MDL focuses on the packaging, flight qualification and testing of laser devices from 0.7 to 10-µm wavelengths that include tunable diode lasers, interband-cascade lasers, and quantum-cascade lasers. The interband-cascade laser (ICL) was invented at MDL and installed into JPL's Tunable Laser Spectrometer (TLS) instrument now operating successfully for the last decade on the Curiosity Rover of the Mars Science Laboratory (MSL) mission. The two-channel Mars TLS instrument has produced high-impact science results that include: the first *in situ* measurements of isotopic ratios in CO_2 that detail atmospheric escape, the discovery of diurnal and seasonal changes in atmospheric methane, the identification of the timing of water loss on Mars through measurements of the D/H ratio, and the determination of isotope ratios in gases evolved from rock pyrolysis.

The enormous success of the Mars TLS has spawned great interest in tunable laser spectrometers for planetary payloads. Very recently, NASA selected the Venus DAVINCI Discovery mission for launch in 2029, with the TLS as part of the atmospheric probe that will descend to the surface to make gas abundance and isotope ratio profiles in concert with an on-board mass spectrometer.

Because of their unique ability to measure low-abundance disequilibrium gases and precise stable isotope ratios, TLS instruments have been proposed on several Discovery and New Frontiers planetary missions, including Mars and Venus balloons, a Saturn probe, and a Ceres and Enceladus Lander. They are also candidate instruments for future Venus and Uranus flagship missions. In addition to targeting high-priority planetary science objectives, miniature TLS instruments have been built for other space applications, including for respiration monitoring (O_2, CO_2 and H_2O) in the new NASA astronaut spacesuit, and on-board the Orion spacecraft. Instruments are also under development for lunar resource utilization.

Dr. Webster, a JPL Fellow and former Director of MDL, pioneered the application of tunable laser spectroscopy to research in such diverse areas as molecular structure, photochemistry, electrical discharge physics, and especially Earth and planetary atmospheric science.

His career-long passion and close collaboration with MDL laser teams led by Drs. Ryan Briggs, Mathieu Fradet, Alex Soibel, Rui Yang and Siamak Forouhar have resulted in one of the most successful technology development infusions by MDL and a stunning portfolio of scientific contributions.

Background: This view shows an image of the Victoria crater on Mars taken by the High Resolution Imaging Science Experiment on NASA's Mars Reconnaissance Orbiter.

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

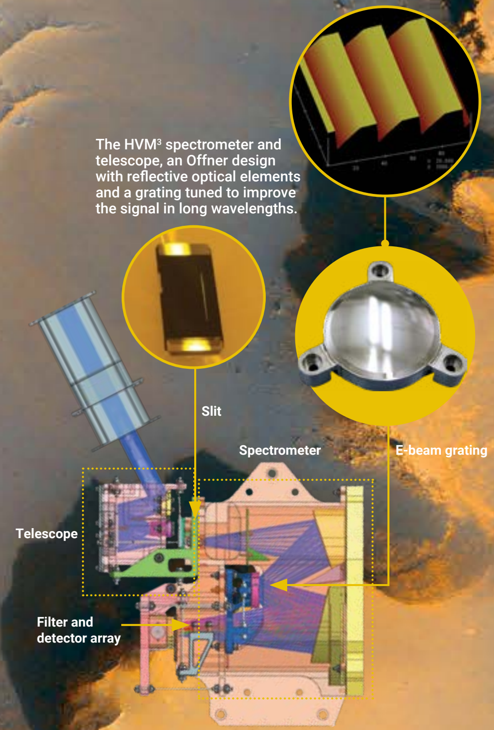
Lunar TRAILBLAZER

Lunar Trailblazer is a Small, Innovative Missions for Planetary Exploration (SIMPLEx) mission and was selected in June 2019 to conduct a 12-month mission study leading to a Preliminary Design Review and evaluation for flight. A Ball Aerospace smallsat in a 100-km lunar polar orbit will carry spectral imagers to detect and map water on the lunar surface and determine its form and local distribution as a function of latitude, soil maturity, and lithology.

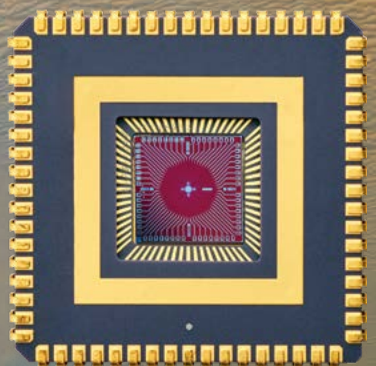
It will also assess possible time variation in lunar water on sunlit surfaces and use terrain-scattered light to determine the form, paying special attention to permanently shadowed regions. In addition, Trailblazer will map lithological diversity at candidate landing sites, which supports the latest Planetary Decadal prioritization of a lunar sample return mission. NASA is so interested in the results that it has brought forward the mission launch date from 2025 to 2023.

MDL is providing enabling technologies for the shortwave infrared imaging spectrometer for the JPL High-resolution Volatiles and Minerals Moon Mapper (HVM[3]) instrument.

A LOW COST MISSION TO DRAMATICALLY EXPAND KNOWLEDGE OF THE MOON'S WATER RESOURCES.



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



64-element SNSPD focal plane array developed at MDL for the NASA DSOC project.

RECEIVER FOR DSOC

The most recent Planetary Decadal Survey identified communications as a potentially major disrupter of solar system exploration missions, especially the Mars program. More generally, the Deep Space Network, which is the only means of communicating with missions, is near its bandwidth limit, and future missions with more-advanced instruments will need to return increasingly large amounts of data. NASA's response was to develop optical communication with lasers, analogous to replacing old copper telephone wires on Earth with modern fiber optics. The Deep Space Optical Communications (DSOC) technical demonstration, the first attempt at optical communication in deep space, will use the Psyche spacecraft and comprises a flight laser transceiver, a ground laser transmitter, and a highly sensitive ground laser receiver developed by MDL.

TECHNOLOGY DEMONSTRATION FOR FUTURE INFORMATION EXCHANGES ON NASA MISSIONS.

PlanetaryScience

Earth Science

The first Earth Science Decadal Survey, "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond", was published in 2007.

Among other major missions, it mentioned HyspIRI (Hyperspectral Infrared Imager) to address a range of priority observation requirements identified by various scientific panels and which included: Ecosystem function; Heat stress and drought; Vector-borne and zoonotic disease; and Surface composition and thermal properties.

HyspIRI is comprised of two instruments, a visible to short-wavelength infrared (VSWIR) imaging spectrometer and a thermal infrared (TIR) multi-spectral imager. The Survey's recommendation led almost immediately to the formation of the HyspIRI Mission Concept Team tasked with studying refining and defining mission possibilities and which made its final report in 2018.

The subsequent Decadal Survey in 2017, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space", defined scientific priorities which could be addressed by instruments similar to HyspIRI. In particular, it identified land surface dynamics and surface hydrology as critical terrestrial phenomena to be monitored by Earth observation satellites, thus endorsing the recommendations of the Midterm Assessment.

ECO-STRESS

The NASA ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission gauges the temperatures of plants in a wide variety of locations and how those temperatures change during the year. The spatial resolution is very high; for example, a single agricultural field could be studied. The mission is monitoring evapotranspiration, the process whereby plants lose moisture to the atmosphere, which is a vital link in understanding the hydrological cycle.

The mission responds to the Decadal Survey question about coupling the water and energy cycles, specifically how the water cycle is changing, including changes in evapotranspiration. The mission deploys the JPL Hyperspectral Infrared Imager (HyspIRI) thermal infrared radiometer instrument, which depends upon MDL's calibration targets and SWIR bandpass filter components.

EMIT

The Earth Surface Mineral Dust Source Investigation (EMIT) mission will be deployed on the International Space Station (ISS) in 2022 and will measure the composition of minerals that become airborne dust. Wind-blown dust occludes sunlight and deposits on many surfaces on Earth. Also known as mineral dust or desert dust, it can influence weather, hasten snowmelt, and fertilize plants on land and in the ocean. Particles from North Africa can travel thousands of miles around the globe, sparking phytoplankton blooms, seeding Amazonian rainforests with nutrients, and covering some cities with fine grit while also absorbing and scattering sunlight.

MDL provides essential components including a grating, slit, and stray-light control.

HyTI

The Decadal Strategy for Earth Observation from Space identified as a priority the monitoring of global hydrological cycles and water resources. This goal is especially important in response to transformations in water's availability and consumption for agriculture due to climate change, land use and population growth and movement. The Hyperspectral Thermal Imager (HyTI), a 6U CubeSat in low Earth orbit (LEO), is a technology demonstration for future thermal infrared imaging spectrometers with high spatial, spectral and temporal resolution.

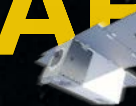
The core of the HyTI instrument is the high-operating temperature (HOT) LWIR barrier IR detector (BIRD) focal plane array (FPA) developed and fabricated at MDL. See page 49 for additional information.

PREFIRE

The Polar Radiant Energy in the Far-InfraRed Experiment 2 (PREFIRE) is an Earth Venture–Instrument (EVI) mission consisting of a pair of CubeSats. Scheduled for launch in 2023, PREFIRE will measure far-infrared (FIR) radiances in the water pure rotational bands (50-600 cm^{-1}) to understand how changing Arctic sea ice, open ocean, and albedo conditions affect the outgoing longwave radiation budget.

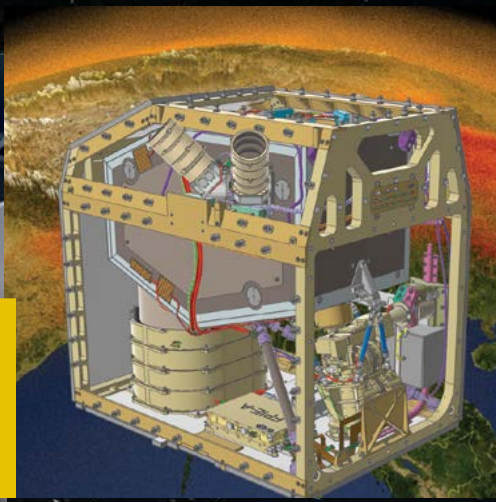
This information is very important because nearly 60% of Arctic emission occurs at wavelengths longer than 15 µm (FIR) that have never been systematically measured. PREFIRE will use a JPL-designed instrument with MDL's thermopile technology. See page 45 for additional information.

CARBON MAPPER

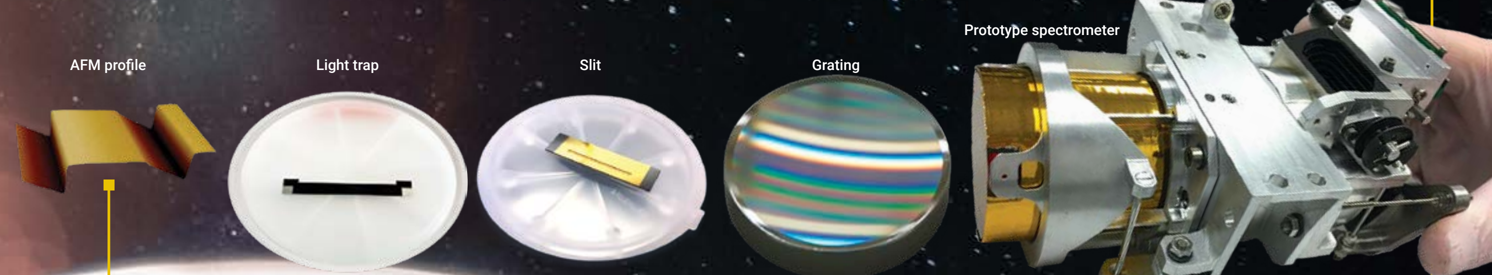


A non-profit organization, Carbon Mapper, has teamed with several partners, including JPL, to develop a revolutionary program to help improve our understanding of and accelerate reductions in global methane and carbon dioxide emissions. By identifying sources precisely, it will enable local action to mitigate emissions.

The first Carbon Mapper satellite is planned for a 2023 launch, and JPL will provide a state-of-the-art hyperspectral imaging spectrometer, a more advanced version of the sort of instrument developed continuously by JPL over very many years. The essential slits and gratings at the heart of the instrument will come from MDL.



The Decadal Survey prioritized. NASA endorsed. JPL responded. MDL enabled.



Earth Science

30 years of MDL innovations for NASA and its partners.

The following summaries are a small selection of achievements, from many possible, that give a glimpse into MDL's essential contributions to the transformational progress of science, technology, and public outreach. The dates are those of the highlights, often made many years after launch or even much later in long-lived NASA missions, conducted either alone or jointly with international partners.

1993

Upper Atmosphere Research Satellite (UARS): First proof of chlorine monoxide destroying the protective ozone layer in the atmosphere.

This breakthrough was achieved using the JPL Microwave Limb Sounder (MLS), one of four chemical-measuring instruments on a satellite launched from the Space Shuttle Discovery. The MLS measured chlorine monoxide, ozone, sulfur dioxide, nitric acid and water vapor.

It depended on its specialized diode receiver technology, developed in the early days of MDL.

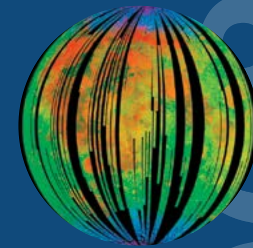
2004

Rosetta Orbiter: The first microwave device in space to study a solar system body.

The Microwave Instrument (MIRO) measured gases from comet Churyumov-Gerasimenko.

MDL's design, fabrication, and delivery of highly optimized GaAs Schottky diodes on very thin silicon nitride membranes using submicron anodes provided sub-mm solid-state frequency sources and radio receivers.

2008



Chandrayaan-1: Discovery of water on the Moon.

India's first mission to the Moon included two NASA instruments, one of which was the Moon Mineralogy Mapper (M³).

M³ was an imaging spectrometer that depended on shaped-groove gratings from MDL to disperse light. It also made the first high-resolution mineral map of the Moon.

2011

Mars Reconnaissance Orbiter: Defining the Gale Crater, the landing site of the Curiosity rover.

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter (MRO) mapped mineral deposits on Mars with visible, infrared and near-infrared light.

The spectrometer was a small instrument that depended on gratings developed and fabricated at MDL using electron-beam technology.

2013

Lunar Atmosphere and Dust Environment Explorer: First laser communication from space.

Part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission was the Lunar Laser Communication Demonstration (LLCD), the first to use light instead of radio waves. It transmitted data over nearly 240,000 miles at a rate of over 600 Mb per second and was enabled by the MDL development of superconducting nanowire single photon detectors (SNSPDs) for optical communication.

2009-2013

Planck: Extracting a high-resolution picture of the early universe from the cosmic microwave background.

Twinned with Herschel for launch, this European Space Agency (ESA) mission, launched in 2009, not only made unprecedentedly precise observations of the cosmic microwave background (CMB) but also determined very precisely the average density of both ordinary and dark matter in the universe, as well as the age of the universe. The satellite had a High Frequency Instrument (HFI) and a Low Frequency Instrument (LFI).

The HFI was enabled by micro-mesh spider bolometers designed and fabricated at MDL.

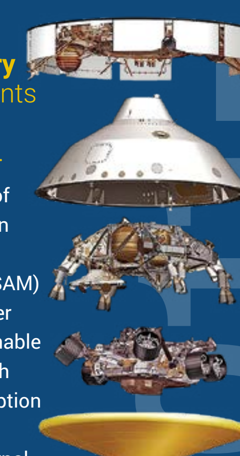
Herschel: Tracking water from molecular clouds to protoplanets.

The Herschel Space Observatory had three instruments, two of which were enabled by MDL technology developments. The development of the Heterodyne Instrument for the Far-Infrared (HIFI) was enabled by the long-term MDL development of superconductor- insulator-superconductor (SIS) mixers and MDL fabricated GaAs Schottky diodes for the primary sub-mm sources.

The Spectral and Photometric Imaging Receiver (SPIRE) depended on micro-mesh spider bolometers designed and fabricated at MDL.

2019

Mars Science Laboratory (MSL): First measurements of methane variation in the Martian atmosphere.



Remote spectral observations of sporadic methane in the Martian atmosphere were controversial. The Sample Analysis at Mars (SAM) instrument on the Curiosity rover included the JPL-developed Tunable Laser Spectrometer (TLS), which made *in situ* infrared (IR) absorption spectrometry measurements. TLS measured background, diurnal variation and sporadic large spikes in methane concentration.

MDL technology developments were integral to this JPL instrument, especially the fabrication and delivery of longer-wavelength interband cascade lasers.

2009

Lunar Reconnaissance Orbiter: The coldest spots measured in the solar system.

The Diviner Lunar Radiometer Experiment (DLRE) is one of six instruments still operating on the Lunar Reconnaissance Orbiter (LRO). The instrument measures surface temperatures on the Moon from orbit.

MDL designed, developed, fabricated and delivered the highly sensitive thermopiles, the heart of the device, which then recorded temperatures on the Moon of less than 30 K (-240 °C).

2020

2020 Mars 2020: Webby Award.

The Mars Public Engagement Team wanted to generate worldwide involvement in the Mars 2020 mission. To that end, its "Send Your Name to Mars" campaign collected more than 10.9 million names from many different countries to be inscribed on special plates attached to the Perseverance rover. This effort won the People's Voice Webby award.

MDL used its electron-beam fabrication facility to write the names on three silicon chips.

A story of continuous innovation & achievement

How MDL works.

As MDL has matured, its staff have learned how to prepare for NASA's ever-evolving technology requirements to answer challenging science questions on future missions.

Among the key lessons learned over the years are securing competed funding over many decades to continually improve MDL's core technology and adapt it to mission requirements. This strategy has given rise to the lab's core competencies, which are tapped to support NASA missions.

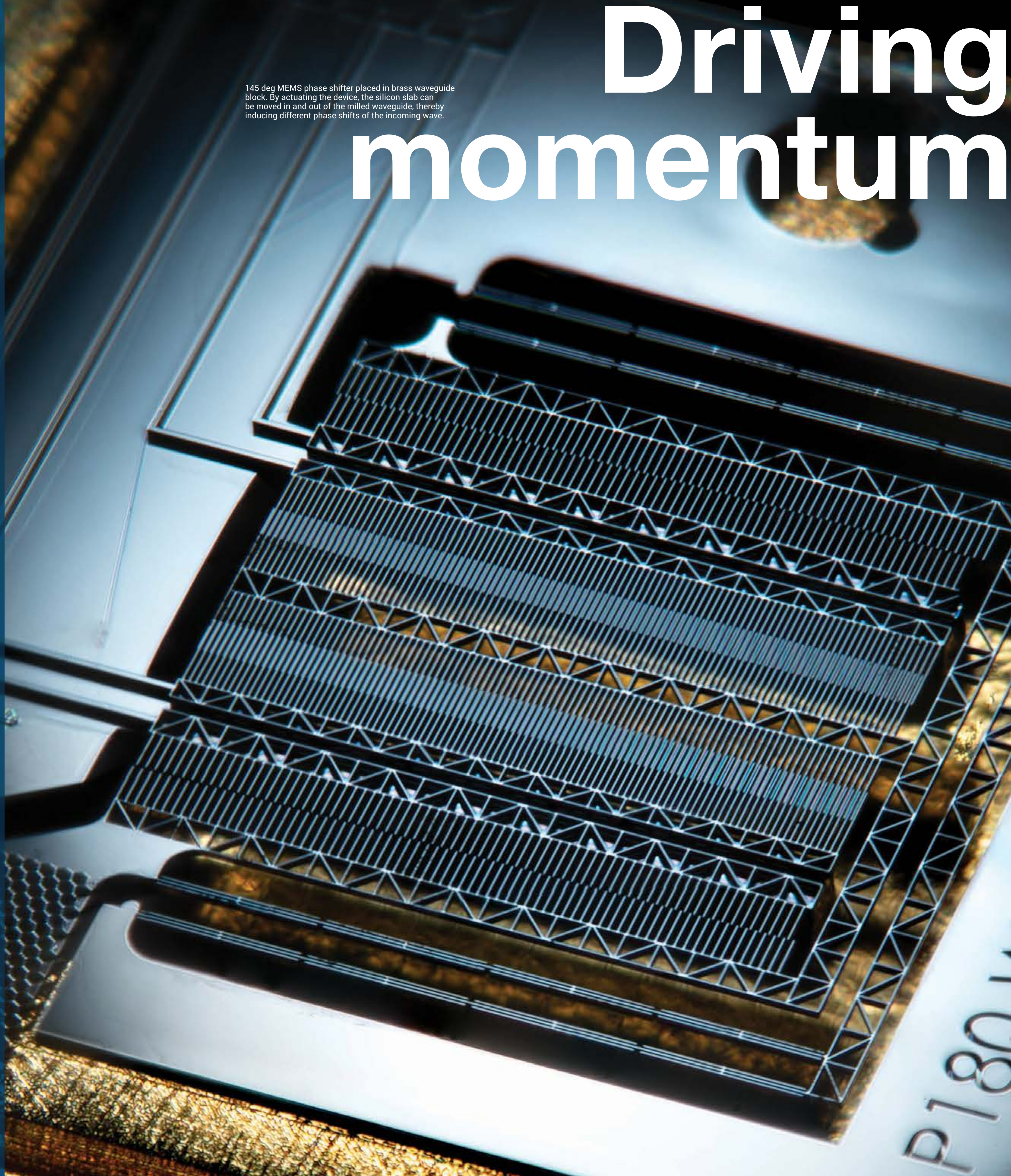
However, if there are already solutions that meet NASA's requirements, MDL will not try to create an equivalent from scratch. Instead, it will provide the custom packaging technology required for the flight implementation of the existing solution.

In a similar vein, MDL staff enthusiastically seek collaborations with outside organizations to incorporate knowledge and facilities that are not available within JPL. These long-term relationships are often of mutual benefit to all involved.

Most importantly, MDL excels because of its people. Attracting and mentoring the next generation of researchers at all levels, from undergraduates to postdoctoral researchers, is the key to refreshing and replenishing researchers in MDL's core competencies.

Additionally, every two years, a group of highly talented and accomplished science and technology leaders from across the nation are invited to critically review the Lab's work and its alignment with NASA's future goals. The feedback of this Visiting Committee is invaluable for maintaining MDL's focus.

Driving momentum

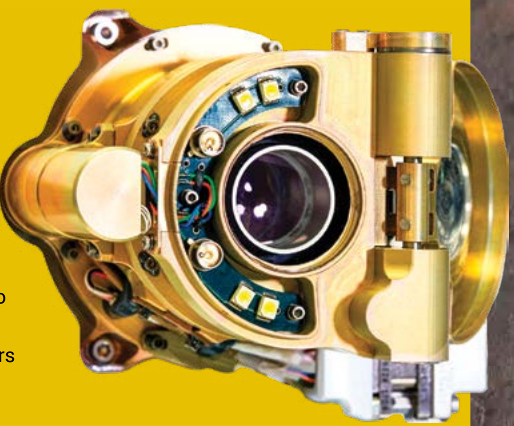


145 deg MEMS phase shifter placed in brass waveguide block. By actuating the device, the silicon slab can be moved in and out of the milled waveguide, thereby inducing different phase shifts of the incoming wave.

FLIGHT INSTRUMENT DETECTORS AND CAMERA SYSTEMS

Devices from inside and outside MDL are packaged for flight and engineered for integration with a payload.

After a 36-year career building and flying cameras at JPL, Mark Schwochert is retiring. In his first project at JPL, Mark contributed to the development of a virtual phase charge-coupled device (CCD) camera for a soft X-ray telescope (SXT) on the Japanese Yohkoh mission, which launched on August 31, 1991. He subsequently worked on the Hubble Space Telescope Wide Field Planetary Camera 2, also known as "the camera that saved Hubble" (1992), Cassini (1997), Stardust (1999), the Mars Exploration Rover (2003), Mars InSight (2018), and most recently the Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument on the Mars 2020 Perseverance Rover (2020).



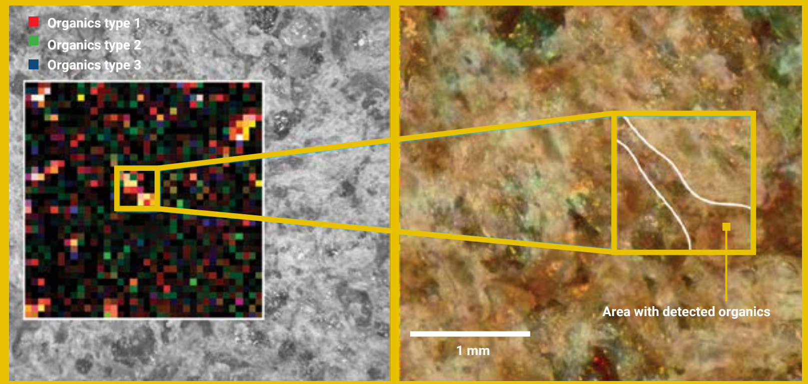
Since 2016, Mark Schwochert has led the Flight Instrument Detectors and Camera Systems group in working with JPL and MDL technologists, engineers, and scientists to design, build, and fly cameras for solar system exploration. The group's vision is to continue JPL's long and successful history of developing and flying advanced detectors and cameras. These cameras enable scientific discoveries in the continuing exploration of the solar system and cosmos by transitioning advanced detector technologies and instrument concepts into space instruments and missions. In 1972, JPL began an advanced imaging program that pioneered the development of scientific cameras using CCDs, which had recently been invented. JPL's visionary investments in detectors and cameras for space exploration contributed to the incredible scientific achievements of the Hubble Space Telescope, Galileo, and Cassini missions.

Fundamental research in semiconductor materials and devices led to the invention of delta-doped CCDs in 1992, only two years after MDL opened.

Over the next 30 years, MDL continued its pioneering research and development of advanced detectors and cameras. MDL developed detectors based on silicon (2D-doped CCDs and complementary metal-oxide semiconductor [CMOS] imaging detectors), III-V superlattices (quantum well infrared photodetectors [QWIPs], high operating temperature barrier infrared detectors [HOTBIRDs]), and superconducting materials (transition edge sensors and microwave kinetic inductance detectors) to deliver unprecedented sensitivity across the electromagnetic spectrum, from X-rays to the far infrared.

However, invention itself is insufficient to produce a flight instrument. MDL and others outside MDL often produced devices that were useful but unsuitable for missions. Therefore, a significant part of the Flight Instrument Detectors and Camera Systems group's work involved adapting potentially suitable devices, packaging them for spacecraft deployment, and engineering their systems to ensure their integration into the overall payload meeting stringent flight deliverable requirements.

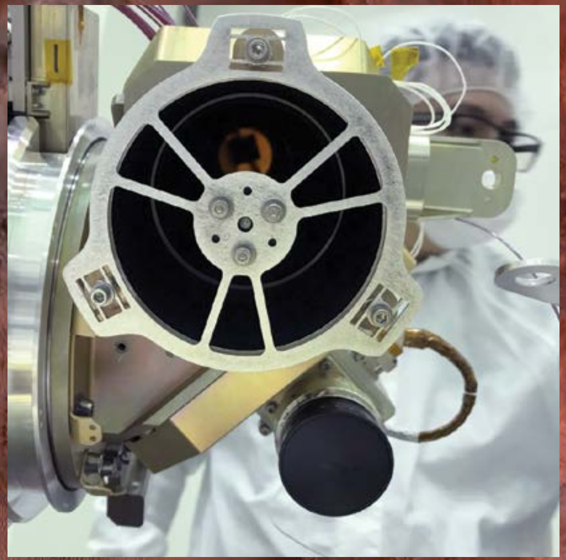
Using specialized knowledge and expertise in flight hardware development to overcome the many challenges of operating high-performance cameras in harsh space environments, the group has built, tested, and delivered context cameras for the Orbiting Carbon Observatory (OCO-3) instrument (International Space Station, launched 2019), the Enhanced Engineering Cameras (EECAM) and entry/descent/landing (EDL) commercial camera system for the Mars Perseverance Rover (launched 2020), the Near-Earth Asteroid Scout (NEAScout) CubeSat mission, and the Surface Water and Ocean Topography Camera (SWOTCam, targeted for a November 2022 launch). Even as Mark retires, his group is carrying his vision forward by contributing to several future opportunities, including single-photon-counting cameras that are currently being built and tested to study exoplanets on the Nancy Grace Roman Space Telescope, the Mars Sample Return (MSR) mission, a game-changing technology program to develop a general-purpose high-resolution camera for extreme environments (LunarCam), the CubeSat Infrared Atmospheric Sounder (CIRAS), multiple NASA Medium Explorer (MIDEX) proposals, and a new extreme ultraviolet telescope concept for the Geostationary Extended Observations (GeoXO) satellite system.



SHERLOC's view of organics within garde abrasion patch.

Mark Schwochert accepting the Manned Flight Awareness, Award of Merit in 1989.

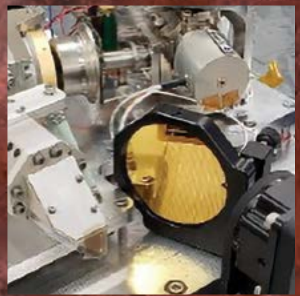
LEFT: The Scanning Habitable Environments with Raman and Luminescence for Organics & Chemicals (SHERLOC) is an arm-mounted, Deep UV (DUV) resonance Raman and fluorescence spectrometer utilizing a 248.6-nm DUV laser and <100 μm spot size. SHERLOC enables non-contact, spatially resolved, highly sensitivity detection and characterization of organics and minerals in the Martian surface and near subsurface.



OCO-3 Internal context camera (ICC).

OCO-3 external context camera.

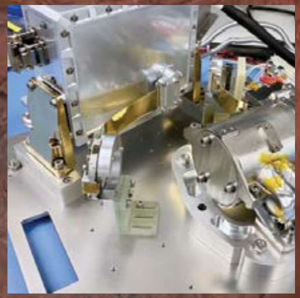
Perseverance rover acquired this image using its onboard Right Navigation Camera (Navcam).



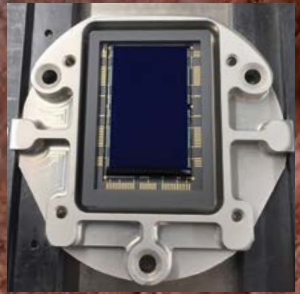
Cubesat Infrared Atmospheric Sounder (CIRAS) test unit.

Mars Perseverance rover landing on Mars. This picture, published on February 19, 2021, was taken by the ruggedized commercial EDL camera system.

Roman Telescope CGI cameras.



Roman CGI focal plane array, with Te2v CCD311 electron multiplying detector.



OCO-3 External Context Camera (ECC) image overlaid with a circular Internal Context Camera (ICC) image.

"Invented elsewhere" is not a pejorative term at MDL

DELTA-DOPED SILICON DETECTORS

MDL has provided numerous creative solutions to challenging problems during its 30+ year history. A classic example is the invention of delta-doped silicon detectors, a technology developed initially in response to instabilities in detectors produced for the Hubble Space Telescope's Wide Field/Planetary Camera (WFPC).

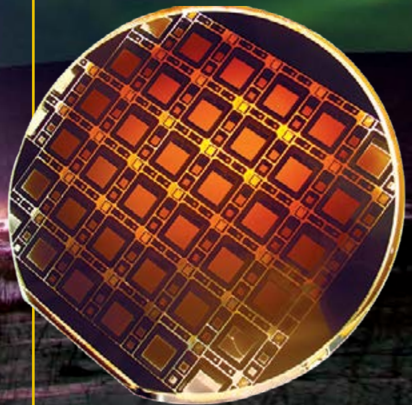
In addition to enhanced sensitivity to light, delta-doped detectors are also excellent particle detectors. The background image shows the 2012 launch of the Magnetosphere-Ionosphere Coupling in the Alfven Resonator (MICA) sounding rocket from Power Flats, Alaska. MICA, a heliophysics mission, included the Low-energy Electron Spectrometer (LEES) instrument, which used a delta-doped silicon CCD to detect electrons with energies in the 10^2-10^4 eV range.

During system-level thermal-vacuum testing of the WFPC, quantum efficiency hysteresis (QEH) was identified. Tiger team members Drs. Paula Grunthaner, Frank Grunthaner, and Michael Hecht had been working on the development of low-temperature growth technology for silicon molecular beam epitaxy (MBE) as a way to improve doping at heterojunction interfaces and allow for epitaxial growth on substrates with existing device structures. They postulated that these low-temperature MBE processes offered a potential solution to the stability issues plaguing the WF/PC-I detectors.

The team proposed and received JPL Director's Discretionary Fund (DDF) funding to explore their solution and hired postdoc Michael Hoenk to develop the process. Initial experiments focused on passivation by three-dimensional doping, but calculations suggested that the dopant concentrations required to pin the band edge and properly passivate the silicon surface far exceeded the saturation limit.

Contemporaneous reports had highlighted delta-doping as a potential solution to this problem. In delta doping, atomically thin monolayers of dopant atoms are separated by layers of un-doped host material; thus the dopant profile resembles the mathematical delta function.

Dr. Hoenk developed a new, low-temperature MBE process for delta-doping silicon detectors, a solution to device passivation. The first-attempted delta-doped devices exhibited the reflection-limited response, meaning their sensitivity spanned not only the visible and near-infrared (NIR) wavelength range but also the ultraviolet (UV) and X-rays!



JPL's delta-doping and superlattice-doping processes can be applied at the wafer level for substrates as large as 200 mm (8 inches) in diameter.

These groundbreaking results were published in 1992, and subsequent publications demonstrated the stability of delta-doped detectors under various illumination and thermal conditions, as well as their long-term (years) performance.

UV detector development focused on silicon-based devices but needed to overcome poor detector sensitivity. Delta-doping results in the reflection-limited response: photons not reflected from the silicon surface are absorbed or counted by the detector. Therefore, antireflection (AR) coatings were used to mitigate reflection losses and improve sensitivity: quantum efficiency (QE) in the near UV increased from 30% to > 50%. The results were published in 1994. The coatings' design and deposition techniques have advanced to include a variety of materials, as well as multiple layers, giving record-breaking QEs spanning the UV range. These improvements are critical for projects like FIREBall-2 (described on page 41).

A second challenge to be faced was detector flatness. Backside illuminated detectors must be back-thinned to remove the photo insensitive bulk silicon and reveal the photosensitive epitaxial silicon. The very first delta-doped devices were frame-thinned; that is, a very thin (10-15 μm), fragile membrane supported by a thick (~500 μm) frame; this resulted in a wavy, "potato-chip" shape that could be seen in the resulting images. As silicon manufacturing techniques evolved, and covalent wafer-to-wafer bonding became industry standard practice, the JPL team transitioned as well. The wafer bonding process allows for the production of large-format devices with flatness on the order of only a few microns!

Additional important advancements include the development of superlattice doping in 2009 and device-integrated UV bandpass filters in 2014. In superlattice doping, multiple delta layers are incorporated into the deposited structure, providing additional stability in harsh environments, and is critical for applications in which the detector may be subject to surface damage (e.g., deep UV or extreme UV radiation). The added delta layers offer protection against surface damage effects.

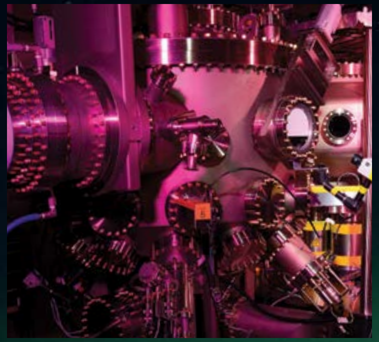
Invented in the 1990s at MDL with support from JPL and still yielding major returns on the investment.

UV bandpass filters allow UV light to penetrate while blocking visible light, which is critical for applications where UV signals of interest are present in a high visible background, as in the SPARCS mission (described on page 40).

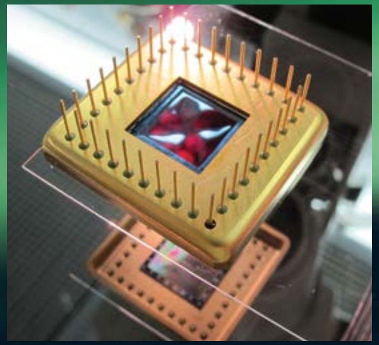
Originally, JPL performed only the MBE processing and relied on industry partners for all other fabrication steps, which limited the extent to which devices could be customized. While still working with industry and within national borders, MDL expanded its in-house capabilities to be able to respond to mission-specific applications. JPL investments, including the purchase of a new silicon MBE and atomic layer deposition (ALD) equipment, have also allowed for high-throughput, wafer-scale processing.

Continued support of the development of delta-doped detectors has now resulted in the technology being baselined for a variety of mission types, (e.g. FIREBall-2 and SPARCS). Furthermore, during the past two years, the UV Detector team has embarked on a large-scale manufacturing qualification effort in which JPL works closely with industry partners to qualify the end-to-end manufacturing process. As part of this collaborative work, a statistically significant number of delta-doped detectors are produced by applying JPL standard processes to a lot run (24+ wafers) comprising two types of scientific charge-coupled device (CCD) designs (electron-multiplying CCDs and conventional read large-format CCDs). Detectors produced from this process are then packaged, tested and evaluated through established Lot Acceptance Test (LAT)-equivalent steps routinely used for flight detector qualification. The ultimate goal of the effort is to reach Grade-1/Class S status for delta-doped detectors, paving the way for future UV missions.

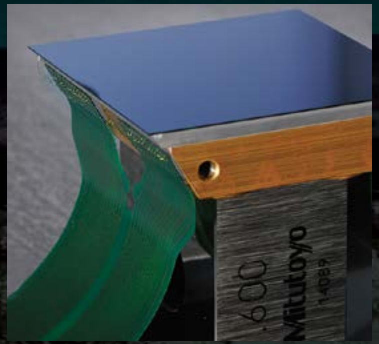
This image was obtained by the Hubble Space Telescope's WF/PC-II using Lumogen®-coated CCDs to downconvert UV photons to visible wavelengths. With delta doping, UV photons are directly detected, eliminating the need for Lumogen.



MDL's Gen200 MBE system enables production-scale passivation of backside-illuminated detectors.



This early example of a delta-doped and AR-coated CCD which achieved world-record quantum efficiency in the ultraviolet was demonstrated using frame-thinned Cassini device spares.



Large-format delta-doped and AR-coated detectors delivered to Caltech's Palomar Observatory as guide and focus detectors for the Wafer Scale Imager for Prime (WaSP) Instrument and the Zwicky Transient Facility.

MDL makes a difference.

MDL products support JPL's strategic mission and business base, providing novel and unique technologies that are the cornerstone of competitive proposals and successful NASA missions/projects.

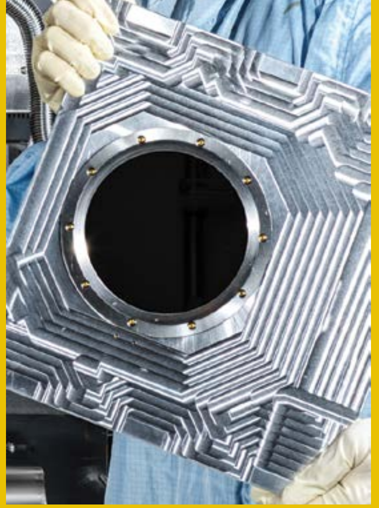
MDL is a unique, multi-user semiconductor processing facility at JPL. It was conceived of and opened over 30 years ago to fulfill an important role in NASA's technology development portfolio by building on JPL's existing facilities and expertise.

Scientific progress may often be limited by an inability to test theories via observation. However, improvements in resolution and sensitivity at all wavelengths have continued to expand our knowledge of the Earth, solar system and universe. MDL has contributed to this progress by inventing, building, and testing proof-of-concept microdevices that enable new discoveries. Its professional engineering staff use its facilities to take these demonstrations and deliver fully fabricated flight microdevices for instruments, such as landers, space telescopes, and spectrometers, which support NASA's space missions.

Academia can create novel microdevices. Industry can provide many space-qualified commercial-off-the-shelf (COTS) components with exact specifications and well-characterized performance. However, MDL is unique in its ability to bridge the gap between academia and industry to produce flight-qualified microdevices and, in some cases to invent novel approaches, as well.

Throughout its 30-year history, the lab's novel flight microdevices have enabled critical discoveries. For example, the Quantum Cascade Laser (QCL) in the Tunable Laser Spectrometer (TLS) on the Curiosity rover found seasonal cycles of methane on Mars; the spider web bolometers measured the shape and structure of the cosmic microwave background from the Big Bang on the Herschel and Planck Space Observatories; and the Roman Coronagraph Instrument and JWST NIRCAM, enabled by MDL electron-beam-fabricated masks, will facilitate future exoplanet observations and discoveries.

Since its inception, MDL has made countless major contributions and overcome seemingly insurmountable challenges in achieving its goal of inventing, developing and delivering new and unique technologies and devices to obtain new scientific measurables for JPL and NASA. MDL will continue to do so for the next 30 years and beyond due to the core competencies it has developed.



E-BEAM LITHOGRAPHY & DIFFRACTIVE OPTICS

Electron beam (e-beam) technologies are at the core of MDL, and they include state-of-the-art nanolithography and the development of new techniques to fabricate unique components for many JPL instruments. For over three decades, e-beam lithography has been an enabling technology for MDL.

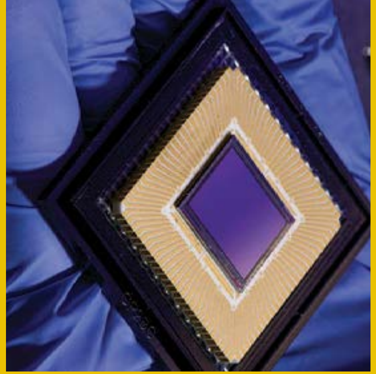
MDL has delivered gratings and/or slits for multiple flight spectrometers, including Hyperion (Earth Observing-1), the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), (Mars Reconnaissance Orbiter), Artemis (TacSat-3), and the Moon Mineralogy Mapper (Chandrayaan-1), as well as airborne spectrometers, including the Airborne/Visible Infrared Imaging Spectrometer (AVIRIS), the Airborne/Visible Infrared Imaging Spectrometer-Next Generation (AVIRIS-NG), Carnegie Airborne Observatory (CAO), the National Ecological Observation Network (NEON) spectrometer, the Hyperspectral Thermal Emission Spectrometer (HyTES), the Portable Remote Imaging Spectrometer (PRISM), and the Ultracompact Imaging Spectrometer (UCIS).

More recently, optical components have been fabricated and delivered for instruments on the Perseverance Mars rover: an ultraviolet grating for the Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument and two spot-array-generating diffractive optics for the Planetary Instrument for X-ray Lithochemistry (PIXL).

SEMICONDUCTOR LASERS & INTEGRATED PHOTONICS

MDL's pioneering work on developing and space qualifying unique semiconductor lasers enabled a new era in planetary and Earth atmospheric studies and is transitioning to the next transformational approach to produce revolutionary new systems with a greater emphasis on integrated photonics. 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. For many years, MDL was one of the few places that could make and qualify semiconductor lasers for space. MDL made the first space-qualified 2.0 µm semiconductor laser for the 1998 Mars Polar Lander.

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.



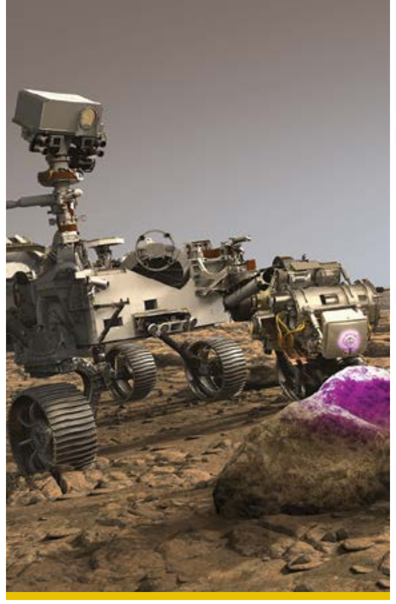
MID-INFRARED DETECTORS

The goal of the infrared photonics technology research area 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 US competitiveness worldwide. At the heart of this area of work are the integrated design, fabrication and delivery of novel infrared (short-wave, mid-wave, long-wave, and very-long-wave) focal plane arrays. Innovations at MDL have enabled observations of our planet in an infrared region just beyond our reach and have facilitated mapping of the world's ecosystems and cloud structures with applications in defense and for natural disasters. In particular, designs and fabrications in new materials have enabled mid-Infrared detectors operating at unprecedented higher temperatures with improved performance.

However, even with such advances, the current state of the art is never sufficient, and establishes a new ultimate goal of developing infrared sensor assemblies that could operate in space solely on passive cooling.

CORE COMPETENCIES

MDL's core competencies depend on facilities and equipment, but more importantly, on the people who use them and their ability to maintain a record of experience and expertise.



CHEMICAL ANALYSIS & LIFE DETECTION

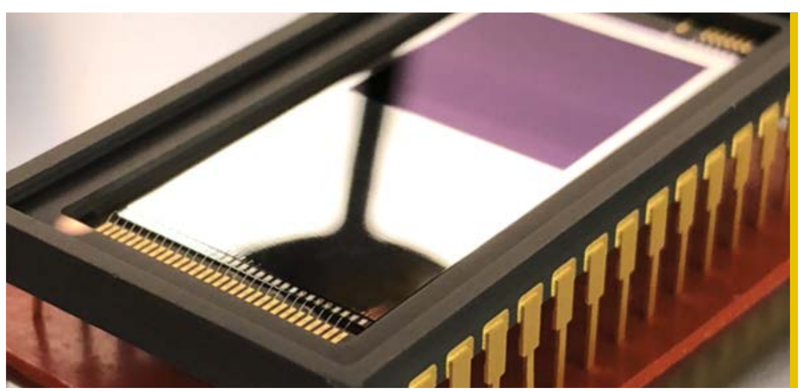
The engineers and scientists at MDL working in this area are pioneering the next generation of spaceflight technologies needed in the search for habitable environments and life beyond Earth. The focus of the group has been on the design of portable instrumentation for *in situ* chemical analysis. A major achievement was developing the Chemical Laptop, a truly portable, battery-powered, automated, and reprogrammable analysis system. This instrument concept can be adapted for a variety of astrobiological targets, like Europa, Enceladus, or Titan. It also serves as a general prototype that could be reprogrammed for Earth-based analyses.

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, which enable precise measurements of the abundance and isotopic composition of specific molecules. Deployable laser spectrometers facilitate an understanding of the structure and dynamics of planetary atmospheres and the chemical composition of gases evolved from rocks and ice. MDL created the 3.3 µm wavelength semiconductor laser at the heart of the Tunable Laser Spectrometer, part of the scientific payload of the Curiosity rover, launched in November 2011. Curiosity has been working ever since and has produced remarkable and unexpected scientific results, including measurements of methane at parts-per-billion levels and the cyclic concentration variation in methane in the atmosphere of Mars.

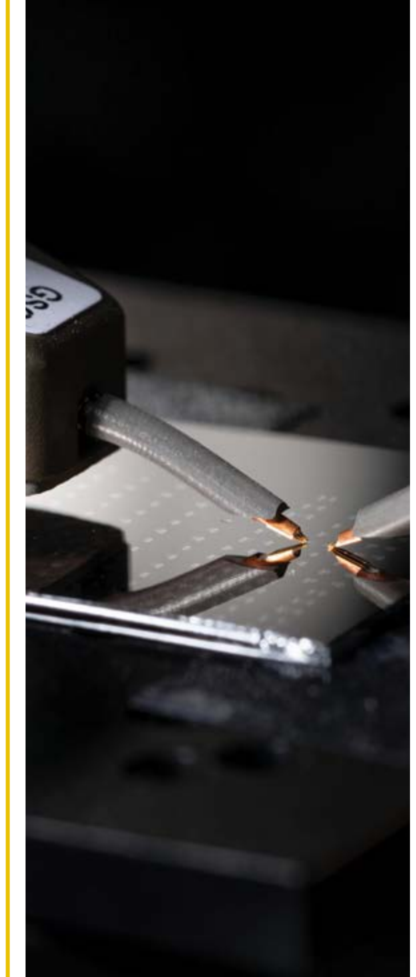
MASS SPECTROMETRY

NASA has included mass spectrometers in the payloads of many planetary missions for *in situ* analysis. Developments at MDL in miniaturizing mass spectrometers have found a completely different application for these instruments: checking the quality of cabin air for human spaceflight. The miniature quadrupole ion trap mass spectrometer (QITMS) has been evolving at JPL since 1994, and in that time, it has established constant performance improvements and met successively smaller size, mass and power requirements. The QITMS is highly sensitive and can make very precise measurements. It can quantify both the concentrations and isotopic compositions of a full range of inorganic species. 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.



UV DETECTORS & SYSTEMS

This effort started as the first demonstration of molecular beam epitaxy (MBE) growth on charge-coupled devices (CCDs) to create high-efficiency ultraviolet (UV) detectors with stable responses and to solve the hysteresis problem that had plagued the Hubble Space Telescope's Wide Field/Planetary Camera 1. It was enabled by innovative MBE processes and concepts developed by MDL scientists Drs. Paula and Frank Grunthaner. From those beginnings, an internationally recognized team of experts has emerged who are leading innovations in UV instrument technologies and instruments, including high-performance detectors, highly reflective mirror coatings, filters, UV scientific cameras, and UV imaging spectrometers. MDL's UV core competencies expanded further via innovations in mirror coatings, gratings, and filters. An early version of the coatings was incorporated into the Scanning Habitable Environments with Raman and Luminescence for Organics & Chemicals (SHERLOC) instrument on Mars2020.

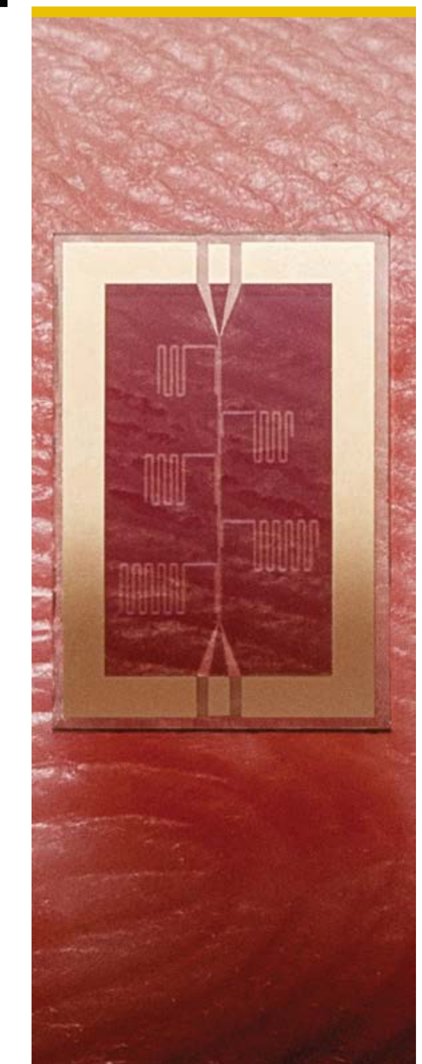


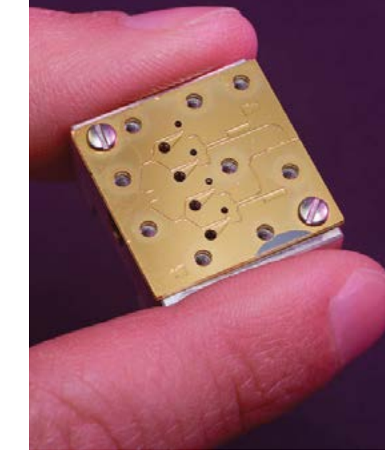
SUPER-CONDUCTING DEVICES

MDL's superconductor technology advances will power communication in the next generation of crewed missions. They will also enable the precise measurement of the smallest things, from single photons to tiny shifts in temperature, in order to answer the biggest questions about our universe. 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, JPL's work on superconducting materials and devices exploited 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.

MEMS & MICROSYSTEMS

Microelectromechanical systems (MEMS) technology continues to shrink the size, mass, and power requirements of vital instruments and systems needed for space missions, thus also shrinking mission cost. Shortly after MDL was formed, the advent of silicon micromachining led to the development of devices such as accelerometers, magnetometers, and thermal infrared detectors. MEMS technology has developed considerably since then, but the aim is always to produce performance equivalent to that of state-of-the-art devices or components with reduced size, mass, and power requirements. This goal has resulted in particularly valuable contributions 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 capabilities, including electron beam lithography, silicon micro-machining, and aluminum nitride depositions by various techniques. However, it is the skillful design and integration of these approaches that marks the successful implementation of MEMS technology.





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. As envisioned initially, MDL delivered many critical instruments. For example, the Microwave Limb Sounder (MLS) instrument first measured OH radicals that play a critical role in ozone destruction. The 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. A terahertz (THz) heterodyne instrument is comprised of an antenna, mixer, local oscillator, intermediate-frequency (IF) amplifier, back-end spectrometer, and computerized numerical control (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.

CORE COMPETENCIES

MDL's leadership, vision, and innovation are delineated in its rise to the challenges of JPL and NASA missions through the establishment and maintenance of its core competencies.

MDL COLLABORATIONS

MDL PARTNERS WITH OTHERS FOR MUTUAL ADVANTAGES

MDL can only produce its incredible range of outputs by working with others outside the organization. Collaborators may bring skills, knowledge or facilities not available within MDL, and they enable MDL to use a larger workforce than it has internally. These collaborations are mutually valuable. If the partner is an academic institution, an undergraduate or graduate student may perform work as part of a research thesis. The project may help support university postdocs and faculty working on problems of mutual interest and advantage. It is particularly valuable to NASA when the principal investigator (PI) of a mission engages MDL collaboratively, rather than as a supplier, to develop and fabricate essential components and use MDL expertise and experience in interpreting results.

Many types of organizations actively collaborate with MDL, including academic institutions, small and large businesses, government labs, and, of course, other NASA centers. Importantly, although not always thought of as such, many of MDL's collaborations are with other groups in JPL whose needs cannot be met except via collaboration with MDL. In some cases, the collaborators do some, if not all, of their work at MDL. This arrangement offers added benefits when working with academic institutions since academic researchers are exposed to MDL's way of working, which is fed back to their colleagues as good, free publicity and may aid in recruitment to JPL. Academic collaborators come from the smallest to the largest institutions, including both public and private schools. Not surprisingly, MDL has many valuable collaborative projects with Caltech, and some JPL staff and professors have positions in both places.

There is not enough space to list all MDL's collaborations, but some specific examples follow.

CALIFORNIA INSTITUTE OF TECHNOLOGY

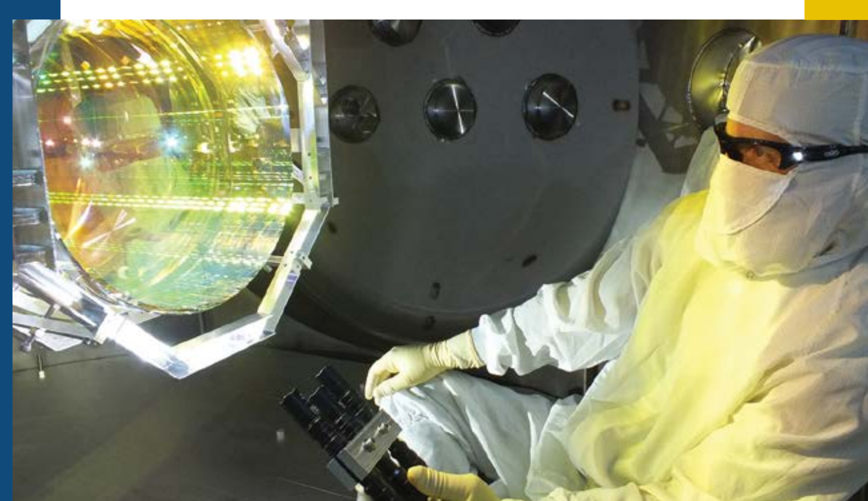
Pasadena, CA

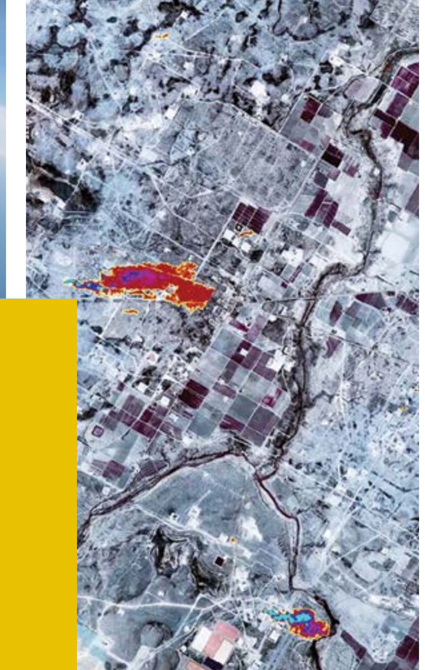
The relationship between JPL and Caltech has many nuances. Although those in JPL know that JPL exists through the Prime Contract between Caltech and NASA to provide a Research Center, many outsiders are surprised to find that they are not two completely separate entities. Despite this, there are many differences, and careful management is needed to ensure no cross-funding support of projects. However, JPL and Caltech have much in common, and there are many routes to supporting joint ventures, both internally funded or as parts of NASA projects or missions. The spectrum of individual interconnectedness is large and includes informal visits, involvement in joint projects, JPL employees holding joint posts at Caltech (as does our new Director), and especially the long-established practice of senior professors taking fixed-term leadership positions at JPL.

In all, there more than 20 active collaborations with at least five different divisions at Caltech, but most are with Physics, Mathematics and Astronomy, followed by Engineering and Applied Science. Other divisions working with MDL include Chemistry and Chemical Engineering, Geological and Planetary Sciences, and the Laser Interferometer Gravitational-Wave Observatory (LIGO) Lab.

Many Caltech students spend time at JPL; one was recently engaged as a postdoc and is now working at MDL. Although not a collaboration in the same sense as the above examples, MDL also receives a large influx of summer interns from Caltech, each spending approximately 10 weeks at JPL and some at MDL. These internships are mainly, but not exclusively, a result of the Caltech Summer Undergraduate Research Fellowships (SURF) program. These interactions also can lead to further involvement as students become aware of the possibilities and opportunities at JPL.

The multiplicity of collaborations between MDL and Caltech are certainly a mutual benefit to both groups.





CARBON MAPPER INC

Pasadena, CA

Carbon Mapper, Inc. is a not-for-profit company that uses remote sensing to pinpoint, quantify, and track methane and CO_2 emissions with such high spatial precision that it can identify a specific individual facility responsible for emissions. It will use these data to fulfill its mission, "accelerating local climate action globally." JPL is part of a team of six partners that is closely involved in the first of what is hoped to be many Carbon Mapper satellites that will make the observations. The satellite will have a 2023 launch and will contribute the essential Carbon Mapper instrument, an imaging spectrometer. In precursor studies using a similar airborne instrument, the Airborne Visible Infrared Imaging Spectrometer-Next Generation (AVIRIS-NG), the same technology pinpointed a methane escape from a leak in a power plant and other leaks at oil and gas production sites. The operators were alerted and repaired the leaks, and a subsequent flight showed that the escape of greenhouse gases had stopped. The company's intention is to make all data publicly available to ensure that both inadvertent and antisocial releases of methane and CO_2 are visible. The company CEO, Riley Duren, personifies the closeness of the collaboration; he has joint appointments as a JPL Engineering Fellow and holds a research position at the University of Arizona.

FLORIDA INTERNATIONAL UNIVERSITY

Miami, FL

Florida International University (FIU) is a top public university with over 56,000 students. Recently, it was ranked first in Florida according to the Board of Governors performance-based funding scores. Its student population is very diverse. NASA is significantly involved in FIU through its Minority Undergraduate and Research Education Program (MUREP), which engages underrepresented populations through a wide variety of initiatives. In particular, NASA funds MUREP Institutional Research Opportunities (MIROs), an agency-wide higher education activity.

In collaboration with FIU, JPL and MDL have been mentoring underrepresented minority and women engineering students as part of the NASA MIRO Center for Research and Education in 2D Optoelectronics (CRE2DO) led by Daniela Radu, an associate professor in the department of Mechanical and Materials Engineering and NASA CRE2DO and NSF PREM Center director.

The program focuses on students pursuing undergraduate or graduate degrees in science, technology or engineering as a way to successfully transition into careers of their choice. Students can learn about MDL technologies, the space environment, and the reliability issues that need to be addressed for a successful space mission.

This program's specific goals include building a cross-sector partnership focused on attracting underrepresented minority and female students in engineering careers. It strengthens the engineering workforce pipeline though a robust recruiting strategy at all educational levels. Most importantly, it enriches underrepresented minority students' capabilities to perform high-quality research through internships at academic partners, NASA centers, and industrial partners. The project has the potential to advance a model that improves the success of underrepresented minorities and women in engineering careers while improving academic mentorship for them as undergraduate and graduate students in engineering programs; the goal is to disseminate this model nationwide.

Actively enhancing the educational and career opportunities of underrepresented minorities and women.

MDL COLLABORATIONS

SELECTED HIGHLIGHTS FROM AMONG MANY COLLABORATIONS

There is insufficient space to detail or even mention many of the outstanding examples of successful and valuable collaborations between MDL and outside organizations. A select few of them are briefly described here to exemplify the range of these cooperative activities.

These are only a few of the possible examples to illustrate the range and value of MDL collaborations.

ARIZONA STATE UNIVERSITY

Phoenix, AZ

The UV Detector team is working with Prof. Evgenya Shkolnik on the Star-Planet Activity Research CubeSat (SPARCS), a CubeSat mission funded through NASA's Astrophysics Research and Analysis (APRA) program.

In addition to its science goal of observing M-dwarf stars, SPARCS will advance the technology readiness level (TRL) of 2D-doped silicon detectors, including both AR-coated and solar-blind UV detectors.

The SPARCS collaboration also uses the team's modular camera electronics. The SPARCS camera subsystem, including high-performance UV detectors, is baselined for several mission concepts currently under development.

USC

Los Angeles, CA

USC has developed novel III-V growth processes on amorphous or polycrystalline surfaces, and the joint goal is to make high-quality templates for growing shortwave infrared (SWIR) detectors directly on readout integrated circuits (ROICs). These detectors would have very high performance and enable a significant amount of new science due to their dramatically lower cost.

D-WAVE SYSTEMS,INC

British Columbia, Canada

This company is the leader in the development and delivery of quantum computing systems software. Since 2005, MDL has been leveraging JPL/MDL superconducting electronic technology (fabrication, measurement, and analysis) and rapid prototyping capability in support of quantum annealing processor development at D-Wave Systems Inc., which is commercializing quantum computing with quantum annealing machines based on two-dimensional superconducting qubit arrays.

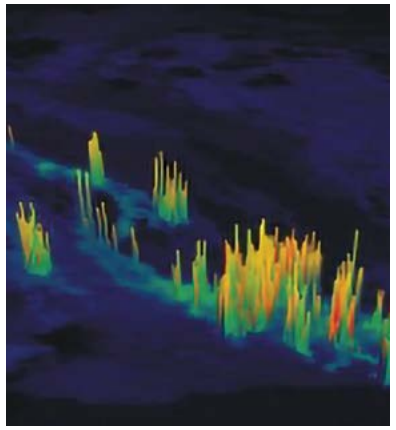
MDL's collaboration with D-Wave emphasizes forward-looking investigations into problems of mutual interest that represent the greatest challenges to D-Wave's continued success. JPL fabricates prototype and test wafers and performs cryogenic measurements aimed at noise/decoherence reduction, novel circuit designs, device/circuit improvement, and fabrication process development.

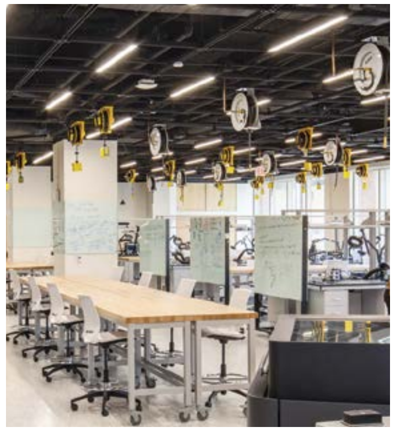
UNIVERSITY OF HAWAII

Manoa, HI

MDL is working with a group at the University of Hawaii to develop smaller size, weight, and power (SWaP) hyperspectral imagers for Earth, lunar, and planetary science applications. Current work includes a NASA Earth Science and Technology Office (ESTO) In-Space Validation of Earth Science Technologies (InVEST) program-funded Hyperspectral Thermal Imager (HyTI) that uses JPL's high operating temperature barrier infrared detector (HOTBIRD) and the university's compact spectral interferometer technology.

This collaboration builds a cross-sector partnership that focuses on attracting underrepresented minorities and women to engineering careers and offers opportunities for recruiting them. It also involves engagement in NASA programs that support underrepresented minority participation.





TEMPLE UNIVERSITY

Philadelphia, PA

MDL has been working with a superconducting material growth group from Temple University, a lesser-known but prestigious school, for many years. Temple's group is the only source of a highly innovative superconducting material that is needed for NASA detector applications. By teaming up, MDL accesses very advanced material structures, while Temple students learn about NASA applications and how best to optimize material properties for NASA applications. This collaboration has been very fruitful, resulting in several peer-reviewed publications and record performance components. MDL has also been able to hire well-trained students from this group.

FERMILAB

Batavia, IL

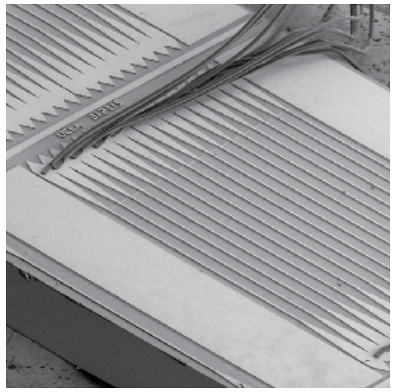
Fermilab was founded in 1969 as the National Accelerator Laboratory. MDL is collaborating with Fermilab on several topics related to superconducting nanowire single-photon detector (SNSPD) development. This includes the development of SNSPD readout circuits in cryo-complementary metal-oxide semiconductors (CMOSs) and the development of scalable SNSPDs for applications in quantum information science and dark matter detection. MDL is also working with Fermilab on developing frequency-domain SNSPD readouts based on field-programmable gate arrays (FPGAs), large-area SNSPDs and integrating these SNSPDs into dark matter detection experiments. Funding is through the Department of Energy.

Further collaboration with this prestigious national laboratory aims to develop and demonstrate quantum capacitance detectors (QCDs) for applications in axion dark matter detection at terahertz (THz) frequencies. Axion dark matter should interact with magnetic fields, generating coherent radiation that can fall in the THz range. MDL is providing QCDs for tests of such theories at Fermilab.

UCLA

Los Angeles, CA

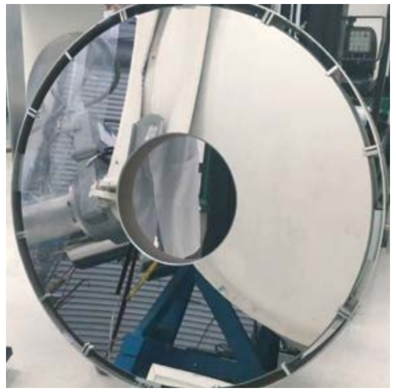
MDL has been collaborating closely with a UCLA group whose leader is a world expert on quantum cascade lasers (QCLs). This collaborative effort with the group, which includes several students, has yielded various novel QCL structures that can be used as terahertz (THz) sources where electronic sources do not work efficiently. This relationship recently led to the MDL employment of a well-trained student from the group. It has also resulted in several publications, along with working prototypes that are currently being used in MDL's laboratory work.



ZECOAT CORPORATION

Granite City, IL

ZeCoat Corporation is a small business that specializes in unique vacuum coatings. MDL and ZeCoat have explored new aluminum evaporation techniques and processes that could be used to provide improved coating performance on next-generation UV space telescopes. Their specific goals are to improve the state of the art in coating uniformity and precision to enable broadband telescope systems up to 6 m in diameter that can meet the stringent requirements of coronagraphic systems in future flagship astrophysics missions.



The most significant impact at MDL is made by its large cohort of postdoctoral researchers, who are supported either through a project or the NASA Postdoc Program. They perform specialized research and often have unique roles as part of various teams. Many postdocs, having experienced life at JPL, are subsequently recruited as employees.

Involving and mentoring the next generation.

Ioana Craiciu

I have been working on superconducting nanowire single photon detectors (SNSPDs) since joining JPL as a postdoctoral scholar in September 2020. SNSPDs are highly efficient low-noise detectors that measure light at the single-photon level, which makes them useful in a variety of applications, from deep space optical communication to quantum information. We are always pushing the frontier with SNSPDs by extending the range of wavelengths they can detect, making them faster, and building larger arrays.

Microdevice engineers fabricate these detectors at MDL, and my role is to measure them. Detectors based on superconducting materials must be cooled in order to operate – in our case to 1 K – meaning that all testing is done inside helium cryostats. We often need to use custom-built electronics, such as amplifiers and time-to-digital converters, to keep up with the performance of the SNSPDs. Once I measure a device, I work closely with other members of MDL to iterate on the design.

Recently, we developed a detector comprising 32 superconducting nanowires; it can efficiently detect single photons at 1550 nm at rates up to 1.4 gigacounts per second and with a timing jitter of less than 100 picoseconds. Such a detector would be invaluable in high-speed quantum communication demonstrations, where data rates are high and each bit of information is encoded in a single photon.

John Femi-Oyetoro

I joined MDL in late 2021 as a postdoctoral fellow in the MDL Next program. Since joining JPL, my primary focus has been the design, process development and fabrication of shortwave infrared (SWIR) photodetector devices. This research has a focus in Astrophysics by demonstrating high quality, SWIR photodetectors grown directly on silicon wafers under conditions that would not damage the read out integrated circuit (ROIC) device (temperatures < 450 °C). In addition, this research addresses the manufacturing complexity of current IR detectors, and the read noise hurdle, which limits sensitivity in low backgrounds in space. I have successfully aided this effort by developing a temperature-based etch recipe for side-growth etching, lithography process for the epitaxial growth, and ALD process for single layer Sn doping of the III-V's, for the enhancement of high-quality single crystal epitaxial growth. If successful, this new technology will dramatically reduce the cost of very large IR focal plane array (FPA) detector in telescopes.

Sven van Berkel

In September 2020, after pursuing my PhD degree in electromagnetics at Delft University of Technology (The Netherlands), I joined JPL as an NPP (NASA Postdoctoral Program) fellow. My home here is at the Submillimeter-Wave Advanced Technology (SWAT) group, and Dr. Goutam Chattopadhyay is my advisor. I am developing novel terahertz (THz) antennae (arrays), quasi-optical components and systems for next-generation multi-pixel THz spectroscopy instrumentation.

I am working on a completely revised detection architecture that will enable, for the first time, the development of a large-format THz heterodyne array, potentially containing hundreds of pixels. Scaling this type of detection architecture has been very challenging due to poor coupling schemes of the scarcely available local oscillator (LO) power and a complex integration of the front-end components. In our architecture, the radiofrequency (RF)- and LO power are not coupled from one side but from two back-to-back leaky-wave lens antenna arrays, then combined in a silicon micro-machined stack of wafers that contains balanced mixers. Furthermore, I am designing lens-coupled absorbing structures that are fundamental to the most sensitive direct detectors that currently exist: quantum capacitance detectors (QCDs) and kinetic inductance detectors (KIDs), both being developed at MDL. For all these designs, I am using quasi-analytical techniques such as Fourier optics, physical optics, and geometrical optics.

Ghazaleh Kafaie Shirmanesh

In November 2020, I started as a postdoctoral fellow in the MDL Next program. Since joining JPL, my work has been primarily focused on free-space optics and integrated photonics for applications that require low size, weight, power, and cost (SWaP-C) elements. While at JPL, I developed metasurface devices whose subwavelength nature provides unprecedented optical properties not achievable using conventional optical components.

Thanks to these properties, metasurfaces can demonstrate applications in compact, high-performance, and low-cost optical devices and components with very high spatial resolution, creating burgeoning interest in photonic integration at a wide range of wavelengths, from ultraviolet to far infrared. In addition, I have been working on high-resolution spectrometers based on photonic integrated circuits (PICs). I have used fabrication methods such as low-temperature deposition of high-quality thin films and unique etch processes to develop and demonstrate optical and photonics devices such as detector-integrated pixelated filters, spectropolarimeters, and beam-shaping devices. These core technologies can be pursued as the foundation of system-level architectures for astrophysics and Earth science applications, such as remote sensing, multispecies atmospheric profiling, exoplanet detection, and high-resolution imaging.

Kazi Islam

After completing my PhD in physics at Tulane University, I joined MDL in March 2021 as a JPL postdoctoral fellow. My postdoc mentor at JPL is MDL microdevices engineer Dr. Ryan Briggs. Since joining MDL, I have been working on developing micro- and nanoscale photonic devices for various applications.I am building a chip-level spectrometer that will detect atmospheric gases by selectively targeting their absorption lines in the mid-infrared part of the spectrum. I am using bifunctional quantum cascade structures that were previously developed at MDL as tunable lasers and detectors to create this on-chip spectrometer. One of the main challenges of this project is to detect the target gas molecules within the very short optical path length (micrometer to millimeter scale) between the laser and the detector. This shorter path length has the potential to reduce the size and weight of *in situ* spectrometers by orders of magnitude for planetary science and human spaceflight missions. In addition, I am designing and fabricating optical waveguides on multiple material platforms, including thin-film lithium niobate and silicon nitride. These waveguides have many applications in astronomy and astrophysics. For example, periodically poled lithium niobate waveguides are designed to generate broadband high-repetition-rate frequency combs for spectrograph calibration in exoplanet detection.

Dejan Maletic

I am a postdoc in the Planetary Mass Spectrometry Group working on the quadrupole ion trap mass spectrometer (QITMS) for the Supercritical CO_2 and Subcritical H_2O Analysis instrument (SCHAN). The goal of this three-year effort is to (1) develop an interface for the QITMS to couple with the SCHAN and (2) to extend the upper mass/charge (m/z) to 600 to enable life detection via organic biomarker analysis for applications on the Enceladus or Mars lander missions. I completed my BSc, MSc and PhD at the Faculty of Physical Chemistry, University of Belgrade, Serbia. Before coming to JPL, I was a postdoc at the Institute of Physics, Zagreb, Croatia. I have written 12 scientific papers and one patent application.

Miranda Kok

I have a background in analytical chemistry and pharmaceutical sciences. I obtained my PhD from Utrecht University (The Netherlands), after which I did a postdoc at the University of Liège (Belgium). In those years, I developed multiple analytical methodologies to profile and quantify drug formulations, lipoproteins and endogenous metabolites.

Since 2019, I have been a postdoctoral researcher in the Chemical Analysis and Life Detection group under the supervision of Peter Willis. My focus is on the development of innovative methods for the sensitive analysis of organic compounds for future life detection missions. I have developed and optimized a workflow to analyze fatty acids via capillary electrophoresis coupled to mass spectrometry. This workflow allows the detection of distinctive fatty acid biosignatures in bacterial cell cultures, spores and ocean world analog samples. The ultimate goal is to apply this method in the search for life on ocean worlds.

Zuzana Cieslarova

I am a postdoctoral scholar in the Planetary Mass Spectrometry Group at JPL. In my research, I develop protocols for the subcritical water extraction and analysis of different classes of compounds, (e.g. amino acids, nucleobases and carboxylic acids) from microorganisms and analogs related to ocean worlds. I obtained my BS and MS degrees in chemistry from the University of Chemistry and Technology, Prague (Czech Republic), and I received my PhD in Chemistry from the State University of Campinas (UNICAMP, Brazil) in 2016. In 2017 and 2018, I worked as a lecturer and postdoctoral researcher at the University of Sao Paulo (USP, Brazil). During my PhD studies, I developed methods to analyze homocysteine and related amino acids in human plasma using capillary electrophoresis. My postdoctoral project at USP involved various analytical methods (nuclear magnetic resonance, capillary electrophoresis and surface-enhanced Raman scattering) to study hemiesters of carbonic acids.

Tobias Wenger

I started as a postdoc at JPL in 2019 with the goal of developing nanophotonic devices. Specifically, I have been working with dielectric metasurfaces – nanostructured surfaces with the ability to control the amplitude, phase and polarization of light at the nanoscale – and the integration of such metasurfaces with photodetectors to improve detector capabilities. These developments can help enable very compact infrared instruments with small power requirements for Earth science applications, as well as astrophysics. Growing out of this initial work on metasurfaces, I have also been involved in developing metasurfaces for wavefront sensing and control, of high importance for the future direct detection of exoplanets in large-scale observatories. In addition, I have worked on developing plasmonic filters for infrared multispectral imaging, where light filtering takes place in a thin metallic film in which nanoholes of varying sizes are created. Since these filters can be fabricated onto the detector chip itself, this technology will allow on-chip multispectral imaging without any additional optical components (i.e., without gratings or additional filters in the beam path) and thereby significantly reduce the instrument size, as well as increase the number of bands in the instrument. The overarching theme of my postdoc at JPL has been centered around utilizing our ability to create nanostructures in a cleanroom and use this ability to manipulate light in new ways to create devices of interest for future generations of space instruments.

Firat Yasar

Since October 2021, I have been an MDL Next postdoctoral fellow. I have mostly worked on the quantum sensors project, where the focus is on designing a laser optic system that can be used in a gravity gradiometer to cool cesium atoms to below micro-Kelvin temperatures. I have identified and evaluated the fiber optic components that are sine qua non of a laser optic system that will ultimately offer a flight-qualified, compact, and portable solution to the gravity gradiometer. Semiconductor lasers, microelectromechanical system switches, variable optical attenuators, optical couplers, and splitters, are examples of these components. In addition to characterizing these components and designing a breadboard that will serve as a portable platform, I have worked to get them up and running concurrently within the specified operating sequence. In the meantime, I have been working on a revolutionary design concept for X-ray imaging detectors that can provide energy-resolving spectrally and spatially resolved detection. My objective was to develop a design that embodies stacked active layers of different materials for X-ray detection using a laterally positioned charge-coupled device (CCD) array. Currently, I am modeling the device and running Fourier transformations based on time and frequency domain simulations, constructing photonic band diagrams, and analyzing quantum efficiency. I continue to pursue ambitious laser optics research and technology development as successful space missions spark new concepts and methods for gravity-gradiometry-assisted exploration on the Moon, Mars, and other planets. Furthermore, our hybrid X-ray imaging detector development is completely motivated by space telescopes such as NuStar, which has a hybrid X-ray detector as a focal plane.

In addition to postdoctoral researchers, graduate students and undergraduates make research contributions at MDL. Graduate students undertake longer-term efforts and conduct what is very often a major part of their research at the Lab. Each student is associated with an outside academic institution, but an MDL staff member may be a co-advisor.

Additionally, every year, many undergraduate summer interns are recruited. For approximately 10 weeks, these students receive training and work on activities they otherwise would not experience. In return for the investment in training them, MDL receives an additional dedicated workforce that makes material contributions to various projects.

Together, postdocs, graduate students, and undergraduates also contribute to MDL's age diversity.

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. 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.

Dr. Thomas L. Koch
Committee Chair
Dean, James C Wyant College of Optical Sciences, Professor of Optical Sciences, Professor of Electrical and Computer Engineering,
University of Arizona

Dr. Paula Grunthaner
Committee Co-Chair
Retired, Manager of Mission System Concepts Section and former Manager of the MDL Microdevices Section,
Jet Propulsion Laboratory

Dr. Mark G. Allen
Alfred Fitler Moore Professor of Electrical and Systems Engineering; Professor of Mechanical Engineering and Applied Mechanics; Inaugural Scientific Director, Singh Center for Nanotechnology,
University of Pennsylvania

Dr. Eric R. Fossum
John H. Krehbiel Sr. Professor for Emerging Technologies; Vice Provost, Office of Entrepreneurship and Technology Transfer (OETT); Director, PhD Innovation Program,
Dartmouth College

Dr. Olivier Guyon
Astronomer and Optical Scientist at the Subaru Telescope and Professor of Optical Sciences,
University of Arizona

Dr. Alexander G. Hayes
Director, Cornell Center for Astrophysics and Planetary Science; Director, Spacecraft Planetary image Facility, Associate Professor of Astronomy,
Cornell University

Dr. Katheryn B. Helean
Director, Center for Microsystems Engineering, Science, and Applications (MESA)
Sandia National Laboratories, Albuquerque

Dr. Paul G. Lucey
Professor, Hawaii Institute of Geophysics and Planetology,
University of Hawaii

Dr. Susan M. Lunte
Ralph N. Adams Distinguished Professor of Chemistry and Pharmaceutical Chemistry; Director, Adams Institute for Bioanalytical Chemistry; Director, NIH COBRE Center for Molecular Analysis of Disease Pathways,
University of Kansas

Dr. Whitney Mason
Deputy Director, Strategic Technology Office (STO),
DARPA

Dr. Carolyn Mercer
Chief Technologist, Science Mission Directorate,
NASA

Dr. Pamela Millar
Director, Earth Science Technology Office (ESTO),
NASA

Dr. Venkatesh Narayanamurti
Benjamin Peirce Professor of Technology and Public Policy; Engineering and Applied Sciences and Physics, Emeritus,
Harvard University

Dr. David Paige
Professor of Planetary Science,
University of California, Los Angeles

Dr. Albert P. Pisano
Dean, Jacobs School of Engineering,
University of California, San Diego

Dr. Natalie Roe
Associate Laboratory Director for Physical Science,
Lawrence Berkeley National Laboratory

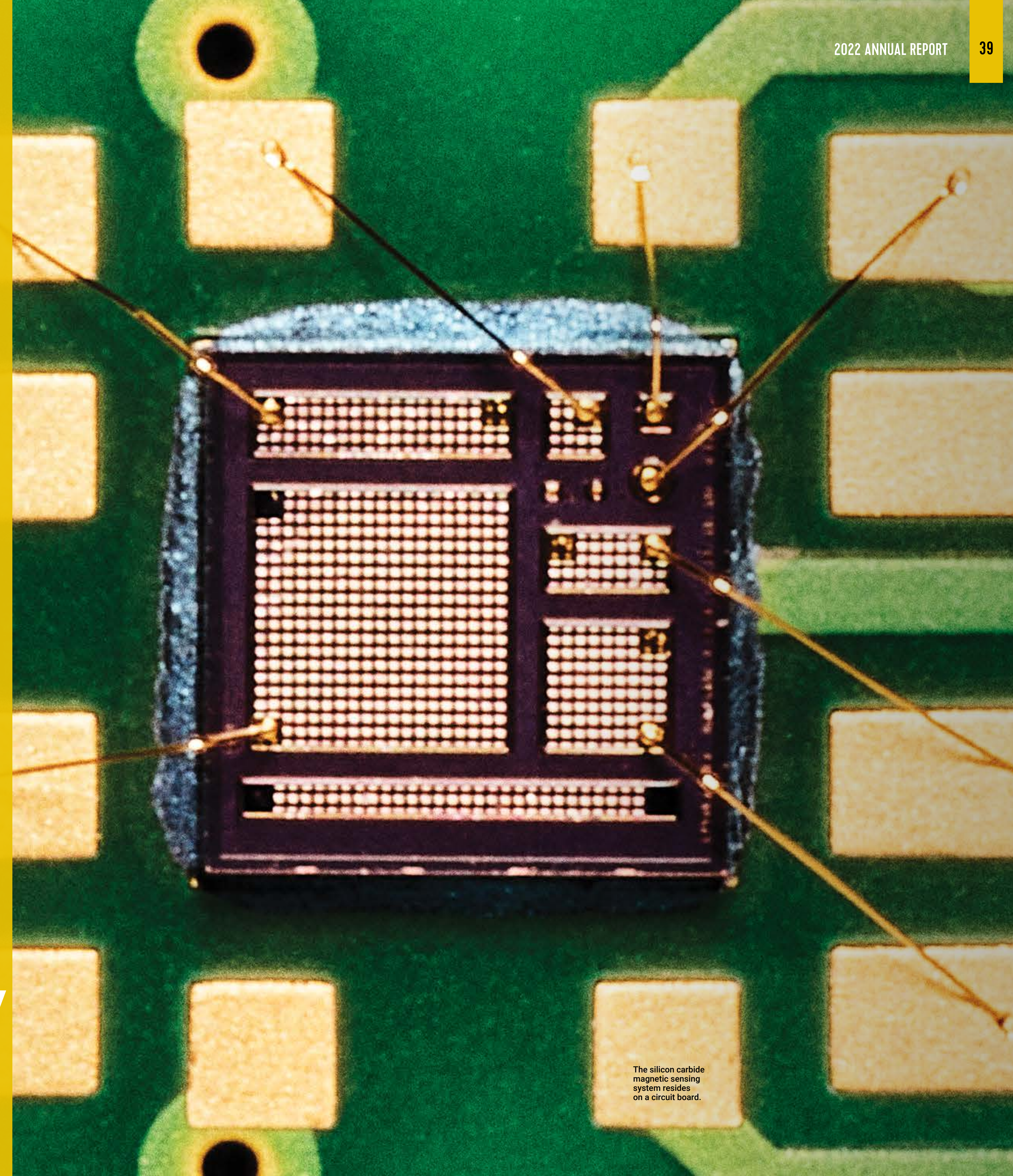
Dr. Jonas Zmuidzinas
Former JPL Chief Technologist, former Director of JPL's Microdevices Laboratory, Director of the Caltech Optical Observatories and Merle Kingsley Professor of Physics,
California Institute of Technology

MDL progresses on many fronts with invention, design, fabrication and delivery.

The engineers, scientists, technicians and staff continued to be very active in developing and producing technology.

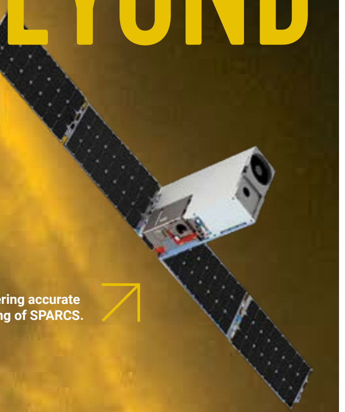
This section includes work that may have been referred to elsewhere in this report but here there are more detailed descriptions as well as some projects not covered.

Technology Progress.



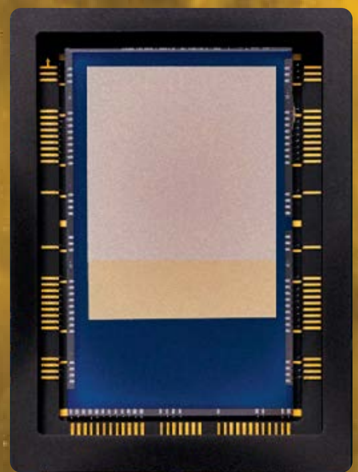
The silicon carbide magnetic sensing system resides on a circuit board.

SPARCS AND BEYOND



Engineering accurate rendering of SPARCS.

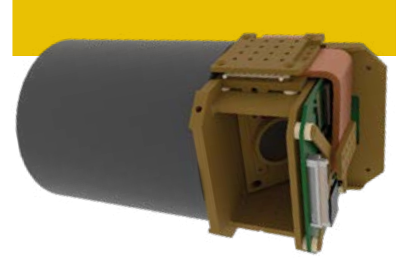
DEMONSTRATING THE LATEST UV DETECTOR TECHNOLOGY AND LOOKING AHEAD TO ITS FURTHER DEVELOPMENT



A charge-coupled device (CCD) array with a butcher-block style linear variable filter that includes an AR-coated region and two regions with visible-blocking UV bandpass filters.

To date, more than 5000 exoplanets have been detected by NASA's Kepler/K2 and Transiting Exoplanet Survey Satellite (TESS) missions, and that number continues to grow. As we move from the era of exoplanet discovery into the era of exoplanet characterization, future missions will rely on technologies and instrumentation that are more capable than ever before. One such mission is the Star-Planet Activity Research CubeSat (SPARCS), a 6U CubeSat mission led by Professor Evgenya Shkolnik (Arizona State University) and funded by NASA's Astrophysics Research and Analysis (APRA) program. The objective of SPARCS is to observe the short-term (minutes) and long-term (days) behavior of M-dwarf stars. M-dwarfs (also called red dwarfs) are the most common exoplanet hosts in our galaxy, with an estimated 40 billion terrestrial planets in their habitable zones — the "Goldilocks" region around a star with ideal conditions for supporting life. However, M-dwarfs are much more active than our Sun, with strong and highly variable ultraviolet (UV) flare emissions than can profoundly affect the habitability of nearby planets. SPARCS observations will be invaluable to constrain the input parameters for photochemical atmosphere models and aid in the discrimination between biological and abiotic sources of observed possible biosignatures.

SPARCS is slated to be the first on-orbit demonstration of the high-performance delta-doped detectors developed at MDL (See article on page 22 of this report). As such, SPARCS is an important vehicle for the technology advancements required for the Decadal-recommended next Great Observatory, which includes the development of large-format, high-resolution UV detectors and solar-blind UV detectors. SPARCS would perform observations in two UV bands using two science detectors, each optimized for their respective bandpass. The near UV (NUV) detector will be a delta-doped charge-coupled device (CCD) with an antireflection (AR) coating optimized for the 260-300-nm bandpass, and the far UV (FUV) detector will be an identical delta-doped CCD with a device-integrated UV bandpass filter optimized for 150-170 nm and offering orders of magnitude of visible light rejection.



3D model of a portion of the SPARCS payload, including 9-cm aperture telescope, a dichroic beam splitter, and two UV detectors. Credit: N. Strubel (AZ Space Technologies).

The technology demonstrations enabled by CubeSat missions like SPARCS pave the way for future, larger-scale missions, including Explorer-Class, Probe-Class and Flagship Missions. In fact, the UV detector technologies to be demonstrated by SPARCS have been baselined for several Explorer mission concepts and served as the basis for Decadal study missions like HabEx and LUVOIR.

The SPARCS detector capabilities are also directly applicable to planetary science. UV observations of solar system objects have been ongoing for 50+ years, and UV instrumentation has been ubiquitous in planetary missions, including Mariner 5 (1967), Voyager 1 & 2 (1977), JUNO (2011), and the Europa Clipper (2024). The improvements in detector sensitivity stability offered by delta-doping technology will directly impact future planetary missions, enabling compact instrumentation with high dynamic ranges and improved throughput.

Future UV instrumentation could take advantage of not only delta-doping but also the optimization enabled by AR and UV bandpass filter coatings. For UV spectroscopy applications, researchers at MDL are exploring sophisticated coating and filter patterning processes to create detector coatings with both "butcher-block" and gradient profiles, with each portion of the detector targeting a specific wavelength range. This approach results in a coating with either a stepwise or a gradually changing detector response from one end of the detector to the other.

By tailoring a detector's spatial response to match the incoming light's spatial distribution, instrument sensitivity and throughput can be increased for all wavelengths, resulting in faster responses and greater scientific return. While these coatings are still in the proof-of-concept demonstration phase, samples have been successfully applied to detectors in laboratory tests. In the future, detectors using these coatings can be optimized for instruments like JPL's Advanced Ultraviolet Imaging Spectrometer (AUVIS), a UV planetary sensor, as well as scientific and engineering instruments targeting other wavelength ranges.

FIREBall-2 gondola suspended from a crane during pre-flight calibration checks at the Columbia Scientific Balloon Facility in Fort Sumner, NM. Background: The Milky Way galaxy. FIREBall-2 enables observations of our galaxy's intergalactic medium. Image credit: P. Balard

FIREBALL-2

LOOKING FOR FAINT EMISSION FROM THE CIRCUMGALACTIC MEDIUM FROM THE STRATOSPHERE

Faint Intergalactic Redshifted Emission Balloon-2 (FIREBall-2) is a suborbital balloon mission designed to discover and map faint emission from the circumgalactic medium of low redshift galaxies (0.3<z<1.0). These observations can improve our understanding of the evolution of galaxies and stars by providing critical insight into the temperature, density, and metallicity of cosmic gases.

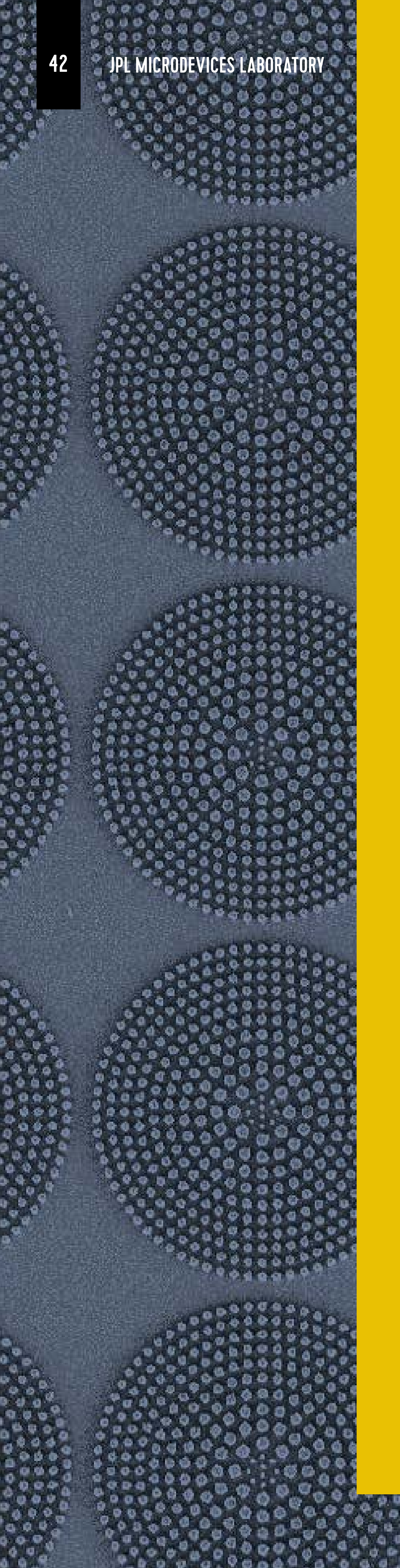
Dual device characterization board shown with a centered calibration photodiode and two delta-doped EMCCDs on the left and right.

The rest wavelength emission/absorption lines of many of important tracer species are in the UV, and for nearby galaxies—including our own—they cannot be observed from the ground. Thus, FIREBall-2 performs from 120,000 feet in the stratosphere, where a narrow UV window (195-225 nm) allows for these important measurements. The FIREBall-2 mission uses a delta-doped electron-multiplying charge-coupled device (EMCCD) as the science detector with the detector's response optimized for the stratospheric UV window using a custom antireflection (AR) coating developed at JPL. This detector demonstrates high quantum efficiency (QE) and very low noise, improving instrument performance by more than an order of magnitude over FIREBall-1, which used a Galaxy Evolution Explorer (GALEX) spare microchannel plate (MCP) as the science detector.

Funded by NASA's Astrophysics Research and Analysis (APRA) program, FIREBall-2 has been an important platform for technology development and advancement. The first FIREBall-2 flight, completed in 2018, successfully demonstrated the full functionality of the detector subsystem in a suborbital environment. The 40 million cubic foot balloon, with its payload, ascended to 39 km but then unfortunately began to descend slowly due to a small hole in the balloon. The flight finished after only 4 hours of dark time and less than 1 hour spent above the minimum altitude for making observations, 32 km. On landing, the payload suffered some damage, which has since been repaired.

A new flight, planned for fall 2022, will demonstrate several system-level improvements, including lower noise detector readout electronics. The team recently secured funding for further development, including two additional flights. Future flights could potentially benefit from ongoing detector advancements, including the next generation of EMCCD technology, Teledyne-e2v's CCD311. The CCD311 has a serial overspill register for improved cosmic ray handling and thus improved photon counting performance. The CCD311 also has a notch filter like that used by Hubble for improved radiation hardness. This detector is baselined as a technology demonstration for the Roman CGI and is also being proposed for future missions.

This work is being undertaken as part of the long-term collaboration between MDL and the Caltech Space Astrophysics Laboratory Group led by Prof. Chris Martin, along with collaborators from the University of Arizona, Columbia University and other institutions in the USA and France.



META-SURFACES

COMBINING THE POWERS OF BULK OPTICS AND METASURFACES FOR COMPACT OPTICAL COMPONENTS WITH SUPERIOR PERFORMANCE

A 1-inch silicon lens with a corrective metasurface fabricated on top. The variety of colors is created from a grating reflection of visible light in the metasurface. The lens and metasurface are designed to focus light in the mid-IR part of the spectrum.

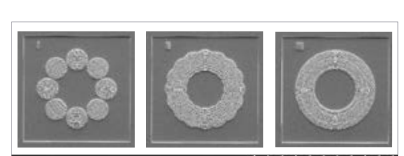
Conventional refractive lenses are efficient and widely available but suffer from many aberrations that dramatically reduce image quality. The standard method for reducing these aberrations is to cascade several lenses together so they cancel each other's aberrations. However, cascading optical elements increases the size, weight and cost of optical systems. Recently, new optical elements based on metasurfaces were demonstrated. The metasurfaces comprise subwavelength nanostructures that control the phase, amplitude and polarization of incident light on very small scales. These properties of metasurfaces offer advantages for creating optical components with superior performance.

The Infrared (IR) Photonics group at MDL has been developing several novel metasurface-based optical elements. Metasurface-based optical concentrators have been developed that are monolithically integrated with IR photodetectors. These concentrators reduce the active area of the detector but maintain optical collection efficiency. This strategy reduces the dark current (and noise), improves the signal-to-noise ratio, and increases the operating temperature of the photodetector. Detectors and focal plane arrays that operate at higher temperatures require less cooling; thus, instruments that use these sensors have a reduced size, weight and power (SWaP). These compact instruments can be deployed on SmallSats, enabling a large variety of Earth observing missions.

Scanning electron micrograph showing three different metasurface-based optical concentrators.

Combining metasurface optics with bulk optics to create hybrid meta-optical parts is a novel, revolutionary approach. Combining the strengths of bulk optics and metasurfaces makes it possible to create large diffraction-limited optical components, which can help reduce the size of optical systems in future space missions and incorporate novel functionality into optical components. As a first step towards hybrid meta-optics, we are working on fabricating a metasurface on a 1-inch lens. We have developed a corrective metasurface for this lens, which makes the lens diffraction limited by reducing its aberrations. We are currently fabricating and testing this hybrid meta-optical part.

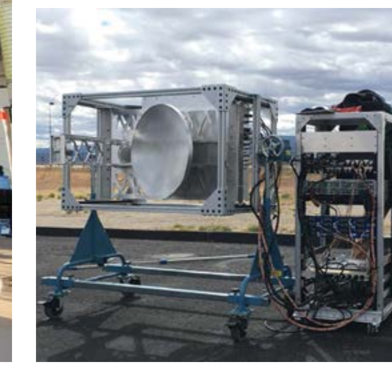
Subwavelength-sized hole arrays in metal films exhibit extraordinary light transmission, i.e., greater transmission than dictated by geometric hole size alone. This phenomenon is due to the presence of certain resonances that allow light at specific frequencies to be transmitted through the otherwise non-transparent metal film. We are using this effect to create highly compact bandpass filters whose properties are determined by the hole array periodicity. Filters with varying passbands can be fabricated on a photodetector array, thus enabling highly compact multispectral imagers for future space missions.



VIPR RADAR INSTRUMENT

MDL DEVICES ENABLE MEASUREMENT OF VAPOR INSIDE CLOUDS FROM AIRBORNE PROFILING RADAR

Fig. 1. VIPR mounted in the P3 bomb bay. The radar's two 15-inch reflector antennae, one for transmitting and one for receiving, are visible, along with the radome covers in the bomb bay plate.



The instrument called Vapor Inside-cloud Profiling Radar (VIPR) has successfully used MDL-produced mixer and multiplier devices for airborne profiling radar. After flying VIPR as a single-antenna system on an unpressurized Twin Otter aircraft in 2019-2020, the JPL team began an Airborne Instrument Technology Transition (AITT) program effort to reconfigure VIPR to fly on a more capable P-3 aircraft. VIPR is participating as a ride-along experiment on the Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) mission, a NASA field campaign. IMPACTS operated multiple meteorological research instruments from a NASA P-3, a NASA-ER2, and multiple ground sites in January and February 2022. The mission of IMPACTS is to study winter storms on the US east coast to improve snowfall predictions. Fig. 1 shows a photograph of VIPR mounted in the nadir port of the P3 bomb bay.

One of the most compelling reasons to fly VIPR with IMPACTS is that VIPR's radar data can be assessed in the context of multiple other instruments onboard the P3. For example, the HALO lidar instrument remotely measures water vapor in clear air, which is highly complementary to VIPR's inside-cloud-sensing modality. Also, dropsondes are frequently deployed from the P3 to measure temperature and relative humidity in the atmosphere below the aircraft. Balloon-borne sondes (weather balloons) are also launched by various ground teams along the P3 flight track.

During a flight off the east coast of the Mid-Atlantic states and New England on January 14, 2022, VIPR collected three-frequency radar reflectivity data of clouds and precipitation. The frequencies were spread over the lower flank of the 183 gigahertz (GHz) water vapor absorption resonance to infer absolute humidity profiles based on differential absorption of the beam by water vapor. Using three frequencies instead of only two (as was done prior to the AITT effort) allows for more-accurate water vapor profile retrieval. Preliminary results of VIPR's reflectivity and inferred water vapor density data over approximately 4.5 hours of flying are shown in Fig. 2.

The vertical black dashed lines in Fig. 2 show where dropsondes were deployed from the P3 to measure atmospheric conditions below the aircraft. The dropsonde data were used to extract *in situ* values of water vapor concentration, which were compared with VIPR's retrieved humidity profiles. There was excellent agreement between VIPR's remote sensing technique and the *in situ* measurements. This preliminary result is encouraging and allows similar instruments to be proposed in the future.

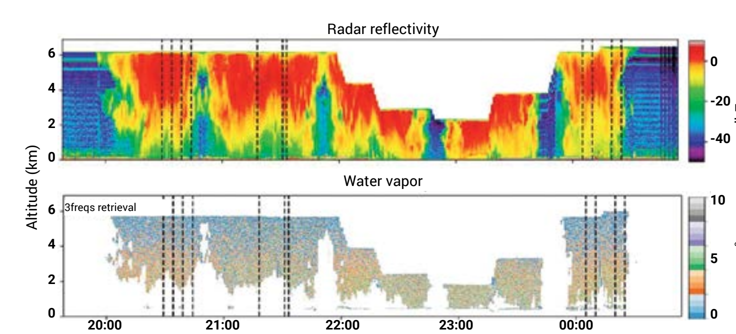


Fig. 2. 167 GHz radar reflectivity profiles (top) and inferred water vapor concentration using a three-frequency retrieval algorithm (bottom). The vertical dashed black lines show the times when dropsondes were deployed from the P3 to sample the atmospheric water vapor in situ.

OWLS

LAYING THE FOUNDATION FOR THE NEXT GENERATION OF LIFE DETECTION INSTRUMENTS

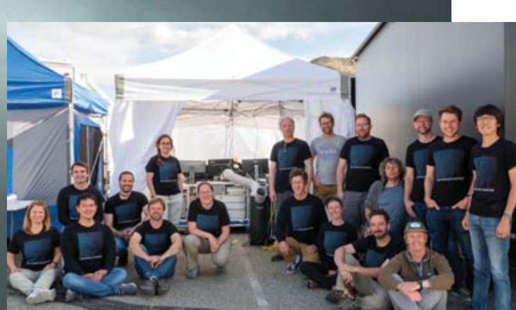
The search for extraterrestrial life is a captivating space exploration topic. The presence of liquid water on Europa and Enceladus makes them prime targets for future missions looking for evidence of life. These missions will require instruments that can identify chemical fingerprints derived from life. Technologies capable of sensitively detecting biomolecules in samples with high salt concentrations will be essential for analyzing samples collected from the surface or the plumes of Europa and Enceladus.

MDL has been rising to this challenge by developing hardware and protocols to meet these needs and developing cutting-edge hardware to perform in situ liquid-based analyses and creating analytical strategies to detect the widest possible range of chemicals.

The hardware is part of the Ocean Worlds Life Surveyor (OWLS), an instrument suite that combines microscopy with chemical analysis, to search for evidence of life at the cellular and molecular levels. Thus, OWLS can confirm the presence of life through multiple means. Chemical analysis is conducted via capillary electrophoresis coupled to multiple detection systems and an array of ion selective electrodes. The use of liquid-based electrophoretic separation in the search for life is particularly powerful, enabling the analysis of myriad soluble organic and inorganic compounds.

Identifying and quantifying each compound in a sample will yield biosignatures that could indicate the presence of life. To cast the widest possible net within the chemical space, three complementary detection systems are used: laser-induced-fluorescence detection (LIF) for the sensitive analysis of amino acids, which the astrobiology community considers among the strongest biosignatures; capacitively coupled contactless conductivity detection (C^4D) to detect inorganic ions and metabolic products; and mass spectrometry (MS) to detect a wide range of organic compounds and identify unknown species in a sample. To prepare a sample for analysis, OWLS also has an extractor system that can break down cells into their chemical components. Each subsystem was first demonstrated in the laboratory before being integrated into OWLS.

The fully automated operation of OWLS was recently demonstrated in the field during a one-week trip to Mono Lake, California. Samples were collected daily and analyzed using all the subsystems in the OWLS suite. Mono Lake is a natural analog to the ocean worlds NASA hopes to explore in the future, so this demonstration highlights the instrument's ability to analyze challenging samples with salt levels similar to those expected to be found on potential future missions.



OWLS team in front of the OWLS suite during the field campaign at Mono Lake.

The OWLS hardware at Mono Lake, CA during a field campaign in June 2022.

PREFIRE

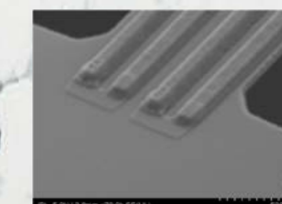
MEASURING ARCTIC HEAT LOSS WITH AN MDL FOCAL PLANE MODULE

NASA's Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) will perform groundbreaking spectroscopic infrared and far-infrared (FIR) measurements from space on Earth's atmosphere. The combination of PREFIRE's spectral range and resolution make this mission the first of its kind. The Arctic is warming faster than the rest of the planet, and climate scientists are challenged to understand this warming process. PREFIRE is designed to make critical measurements that will provide a crucial dataset for climate models to help understand and mitigate climate change.

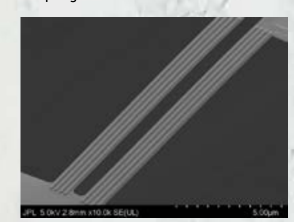
Key to improving climate change predictions is an understanding of the Arctic longwave spectral balance, which shifts seasonally at wavelengths longer than traditional Earth sensors have measured. PREFIRE is designed to probe the Arctic longwave spectral balance seasonally. It follows NASA's trend of building relatively cheap, class D instruments using the CubeSat platform. To access the long wavelengths needed for this science, PREFIRE uses a JPL-designed instrument with MDL's thermopile detector technology embedded within a fully customized focal plane module (FPM) (Fig. 1). The technology is broadband and sensitive, allowing scientists to probe the little-studied portion of the radiant energy emitted by Earth in the FIR (>20 μm) and to seek clues about Arctic warming, sea ice loss, and ice-sheet melting, as well as related changes in cloud cover and surface conditions below. The two PREFIRE CubeSats will make radiometric measurements of the atmosphere between 5 and 50 μm, completely characterizing the variability in FIR emission on scales of hours to months. This spectral data will provide critical insight into surface emissivity, its variability, and the atmospheric greenhouse effect, allowing quantitative modeling of the surface/atmosphere feedback that is hypothesized to amplify the effects of climate change.

MDL has delivered the PREFIRE FPM. The thermopile detector chip was fabricated using the latest bulk micromachining techniques. Fig. 2 shows the back side of the detector chip, where most of the silicon from the chip has been removed using a Bosch etching process and xenon difluoride. This process was necessary to reduce the capacitance between each pixel in the detector array and the input channels on the readout integrated circuits (ROICs).

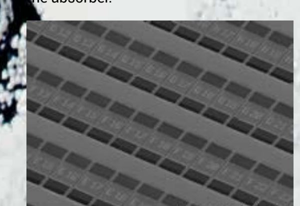
PREFIRE is scheduled to launch in 2023.



c. Bi-Sb-Te thermoelectric wires are patterned on the support beams and act as a thermometer sensing power coupling into the absorber.



b. Each pixel is a suspended silicon nitride absorber with four support beam holding the absorber to the substrate. A black coating called gold black covers the absorber.



a. PREFIRE's array has a format of 64 x 8.

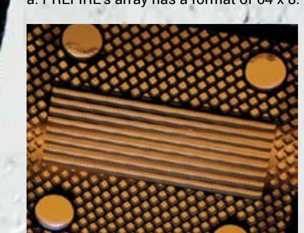


Fig 2. The back of the detector chip, which gives a sense of how we have carved out most of the silicon. This chip is the enabling technology of PREFIRE.

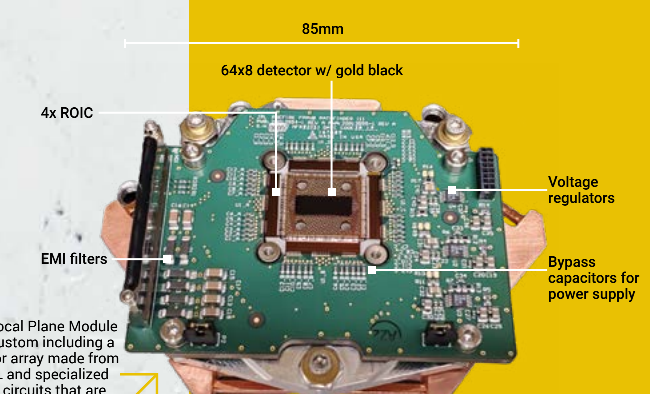


Fig1. PREFIRE'S Focal Plane Module (FPM) is entirely custom including a thermopile detector array made from bare silicon in MDL and specialized readout integrated circuits that are designed to work on PREFIRE.

ALD FOR OPTICS

VERY THIN FILMS USED AS OPTICAL COATINGS YIELD FAST IMPROVEMENTS IN PERFORMANCE

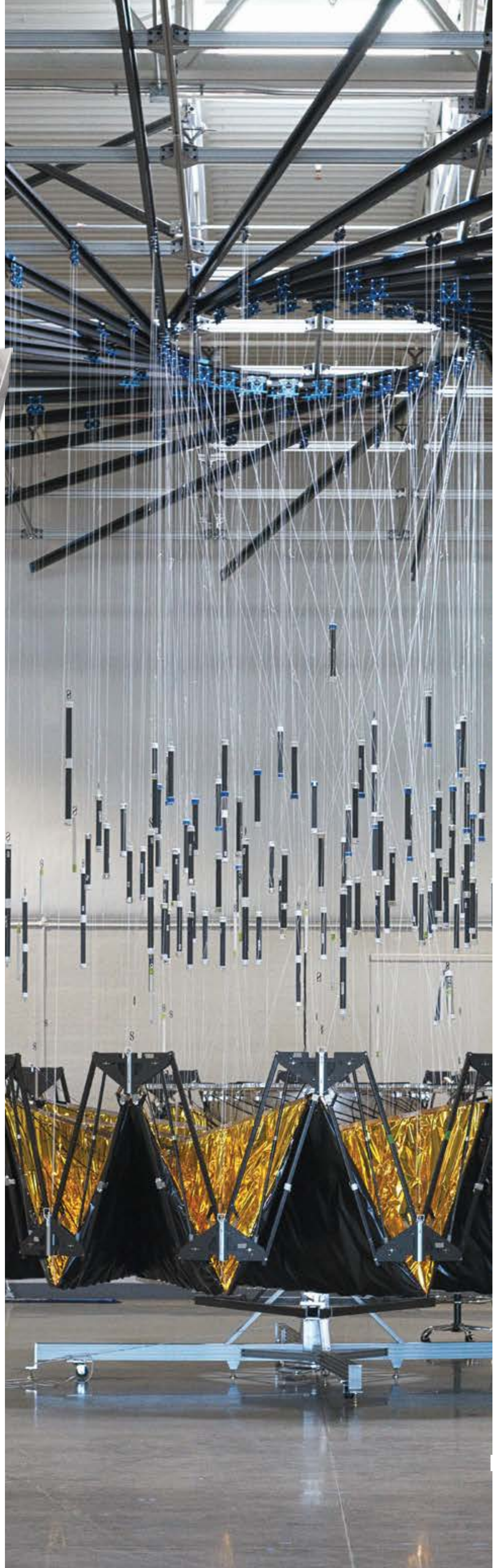
The SPRITE CubeSat primary mirror inside the ALD coating facility at MDL. The primary mirror is 16 x 18 x 5 cm and is the largest optic coated to date in this chamber.

Atomic layer deposition (ALD) is a thin film coating technique that has been widely used by the semiconductor industry due to its unique characteristics, which result in angstrom-scale control over film thickness and exceptional large-area uniformity. ALD has not been as widely used for optical coatings, especially at UV wavelengths, because they require metal fluoride materials that have been less commonly implemented with the technique. Work at MDL has led to several new ALD processes for relevant UV materials like MgF_2, AlF_3, and LiF. These fluoride ALD coatings are useful for many detector-integrated antireflection and filter coatings but also for other optical components like reflective mirror coatings.

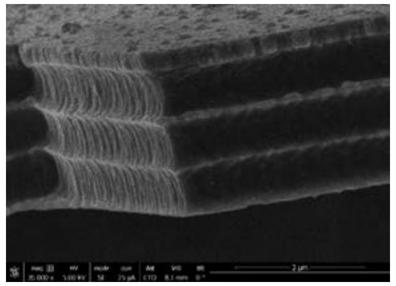
Initial flight demonstrations of the MDL ALD process for mirror coatings have been pursued in collaboration with the University of Colorado Boulder and the Goddard Space Flight Center (GSFC) as a way to enhance the stability of next-generation far UV mirrors. These mirrors use a protective coating of LiF on Al to reach shorter wavelengths than do more typical MgF_2/Al mirrors, but they have the drawback of increased environmental sensitivity. The ALD process is used to apply a thin (<2 nm) encapsulation layer to an existing mirror coating fabricated by conventional methods at GSFC.

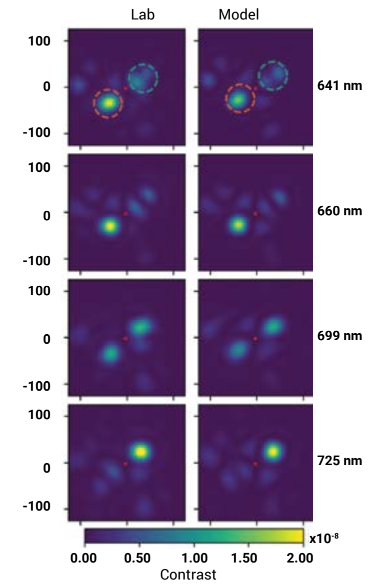
The ALD layer is uniform and dense enough to provide a moisture barrier for the underlying LiF but thin enough to minimize additional optical absorption loss. This process was first validated on mirrors for the sounding rocket program SISTINE (PI: Dr. Kevin France, CU Boulder) in an initial test flight in 2019. In ongoing work, MDLers are coating optics for the orbital CubeSat program SPRITE (PI: Dr. Brian Fleming, CU Boulder), which is expected to launch in 2023. These successful development efforts have also led to the selection of this mirror coating process for the Aspera-Astrophysics Pioneers Mission, intended for launch in late 2024 (PI: Dr. Carlos Vargas, University of Arizona).

Continuing work at MDL uses the ALD process to produce full mirror coatings with improved performance, stability, and scalability relevant to larger future NASA UV missions, including the future large Infrared/Optical/UV (IROUV) flagship recommended by the 2021 Astrophysics Decadal Survey. Ongoing research is also exploring ALD approaches for wedge-filter, dielectric mirror, and dichroic beam splitter coatings operating in the far UV. The new ALD process approaches developed at MDL have also proven relevant to an emerging class of atomic layer etching (ALE) processes that are increasingly utilized in advanced microfabrication methods. These ALE processes have the potential to be adopted into several MDL technologies.



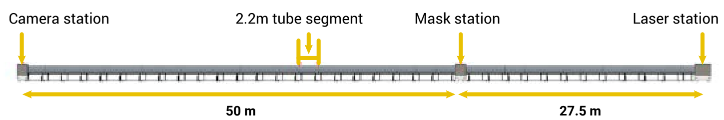
Scanning electron microscope (SEM) image of the corner of a starshade mask. The top layer is aluminum. There are 3 Bosch cycles through the 2 µm silicon thickness. Credit: A. Harness, Princeton University.





Laboratory results compared to model predictions for a starshade mask.

The 80-m-long Starshade Testbed in the basement of the Frick Building at Princeton. The mask is inserted between the camera and the light point source. Photo: A. Harness, Princeton University.



VALIDATING A NEW APPROACH TO ENABLE DIRECT IMAGING OF EXOPLANETS

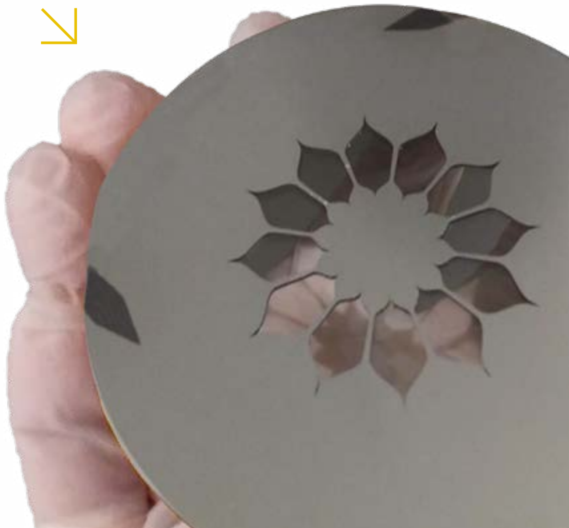
STARSHADE

In the search for exoplanets and attempts to image them, space telescopes have to prevent the intense light from a star from overwhelming the detectors and making it impossible to focus on the orbiting planet, which can be as much as one billion times dimmer. The general solution is the use of a coronagraph in the lightpath as part of the instrument. MDL has a history of making such devices for space telescopes, but it is also using electron-beam lithography and deep reactive ion etching of thin silicon wafers to produce small, laboratory-scale starshade masks for experiments at Princeton University.

NASA is pursuing and testing a concept whereby a flower-shaped starshade can very effectively reduce the intensity of the light from a star even before it reaches the telescope. The device would complement a space-based telescope, and the starshade would be able to position itself precisely between the telescope and the star being observed, blocking the starlight before it reaches the telescope's mirrors. It would have its own propulsion system so that it could position itself away from the telescope at specific points to image different stars' planets.

The large research project based at Princeton involves a smaller-scale starshade to confirm the predictions of system computer simulations. In parallel with this activity, MDL is involved in testing a near-full-scale star shoot system in the lab to validate its performance. These optical experiments use starshades with intentional perturbations built into their design. These perturbations are representative of the type of perturbations possible in a flight design and serve as points of validation for diffraction models and error budgets. Analysis at Princeton of the comparison of modeled results and observations show the results from a starshade with purposely displaced petals and added notches on the petal edges are in agreement with the model to contrast levels below 1 part per billion. Between the perturbation spots, the shadow depth is deeper than 1 part per 10 billion. MDL fabricated the starshade mask.

Starshade mask fabricated at MDL using a 2 µm silicon-on-insulator (SOI) wafer. The diffraction pattern from this mask is designed to form an extremely deep shadow along with a purposely introduced defect pattern resulting from localized micron-scale edge displacements.



LIGO HIGH QE DETECTOR

IN RESPONSE TO PERCEIVED NEEDS, MDL IS ALREADY UNDERTAKING DEVELOPMENT WORK TO MEET CHALLENGING FUTURE REQUIREMENTS

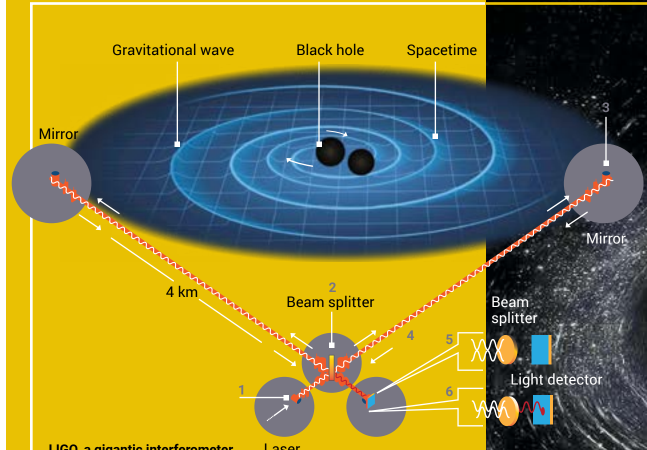
Developments for the Laser Interferometer Gravitational-Wave Observatory (LIGO) and future next-generation gravity interferometers will need much more sensitive infrared (IR) detectors. MDL is already undertaking such development work, and it is likely that knowledge of this development work influenced NASA's Decadal Survey technical development priorities.

To reach the required level of sensitivity needed for the next-generation gravity interferometers, the initial LIGO detectors will have to transition from using silica mirrors at room temperature to using single crystal silicon mirrors at cryogenic temperatures (123 K). Conceptual design studies show that using a 2 µm laser will lead to significant improvements in the coherence time of the light and thus enable the possibility of exploiting quantum entanglement for sub-Poisson limited interferometry. Making such measurements without introducing too much decoherence will require photodetectors that have a quantum efficiency (QE) > 99% at 2 µm.

Gravity wave (GW) detector performance is characterized by sensitivity to a standard candle, in this case a binary neutron star (NS) merger where the two NSs are each 1.4 solar masses.

The "range" of the detector is the distance at which this signal is detectable with a signal-to-noise ratio (SNR) of 8. Increasing the QE of the 2 µm photodiodes in future GW detectors from 75% to 99% improves the GW detector range by nearly 40%. This improvement will increase the volume of space to which the GW detectors are sensitive, as well as the rate of signal detection, by a factor of 2.5. Additionally, improving the sensitivity will allow more-precise measurements of the GWs from merging binary NSs and thus yield more insight into the NS equation of state.

Currently, no detectors meet the main requirements of the next-generation LIGO: QE > 99% at 2 µm with high photocurrent. JPL's IR photonics group recently demonstrated barrier infrared detectors (BIRDs) with QEs of 90% and delivered them to Caltech for testing. We are proposing to demonstrate IR detectors with QE > 95%, which would open the possibility of exploiting quantum entanglement for sub-Poisson limited interferometry. Such quantum measurement capability is applicable to high-precision displacement measurements, as well as future efforts towards quantum dense metrology.

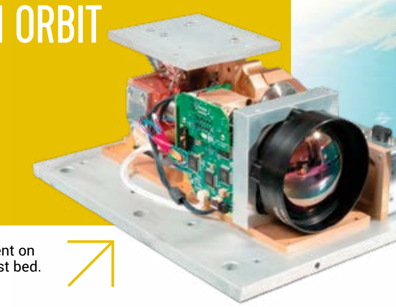


LIGO, a gigantic interferometer

1. Laser light is sent into the instrument to measure changes in the length of the two arms.
2. A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.
3. The light waves bounce and return.
4. A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.
5. Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.
6. If arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

HyTI

A NASA TECHNOLOGY DEMONSTRATION INSTRUMENT FOR MONITORING GLOBAL WATER FROM LOW EARTH ORBIT



HyTI instrument on instrument test bed.

The Hyperspectral Thermal Imager (HyTI) is a 6U CubeSat low Earth orbit (LEO) demonstration as a "pathfinder" that will enable the next generation of high spatial, spectral and temporal resolution thermal infrared (TIR) imagery acquisition from LEO. It will monitor global hydrological cycles and water resources from space and is funded by the NASA In-space Validation of Earth Science Technologies (InVEST) program.

The NASA Decadal Strategy for Earth Observation from Space prioritized monitoring global hydrological cycles and water resources, along with developing a detailed understanding of the movement, distribution and availability of water and its variability over time and space. In addition to helping meet these goals, HyTI will record land surface temperatures to assist NASA in its focus on agricultural water use and crop water productivity.

HyTI is designed with a focus on understanding, modeling, mapping, and monitoring the world's agricultural lands and water resources, but it will also serve in studies on forest fires, volcanoes, and several other applications (e.g., stubble burning on agricultural lands). Climate variability and expanding populations are putting unprecedented pressure on agricultural croplands and the water they use, which are vital for ensuring global food and water security in the twenty-first century. Currently, worldwide, croplands use on average 80-90% of all human water consumption. HyTI data and its derived information products will be invaluable in advancing our knowledge of crop type mapping, crop productivity modeling, crop water use assessments, and crop water productivity ("crop per drop") mapping.

The heart of the HyTI hyperspectral imager is a 640x512 pixel, barrier infrared detector (BIRD) focal plane array (FPA) developed and fabricated at MDL. The net quantum efficiency of the antireflection coated focal plane is 48% in an 8-9.5 µm spectral band. BIRD focal planes have high uniformity, low cost, low noise and higher operating temperatures than previously flown total internal reflection (TIR) focal planes. HyTI also includes a unique Fabry-Perot interferometer developed by the Hawaii Institute of Geophysics and Planetology and a Unibap e2160 heterogeneous onboard computing platform, which promise to achieve fast turnarounds for the processed data and information products. In a 430-km orbit, the HyTI instrument will have a ground sampling resolution of 60 m for up to 50 spectral samples in the 8.0-10.7 µm wavelength range, with a peak signal-to-noise ratio of ~500:1.

Land surface temperature (LST) data have been retrieved from hyperspectral imagery for over two decades. By using one or more of these previously established LST retrieval methods, we believe accuracies of ≤1 K are potentially achievable from HyTI hyperspectral imagery. The primary benefits of demonstrating HyTI's spaceborne hyperspectral TIR imaging capability are: a) Significantly reduced cost for high-spatial-and-spectral-resolution TIR imaging using a 6U CubeSat platform. The low cost of the HyTI LEO mission will also enable high-temporal-resolution, global coverage in the future by putting up a constellation of 25-30 HyTI satellites for well under the budget required for a single, conventional satellite such as a Landsat-8 or Landsat-9. b) New and enhanced scientific capability of hyperspectral TIR imaging with high spatial resolution, which has thus far not been achieved from space. Using a combination of advanced signal processing and sensor fusion algorithms, we will be able to derive very accurate LST values for a wide range of land surfaces (e.g. soil, vegetation, water bodies), and for the first time, HyTI data and information products will be "actionable" at the individual farm level due to their high spatial resolution.

MDL delivered the flight FPA and now, most significantly, has delivered the flight instrument to the HyTI project. HyTI's focal planes and integrated dewar cooler assembly were developed by Drs. Sarath Gunapala, Sir (Don) Rafol, David Ting, Alexander Soibel, Brian Pepper, Arezou Khoshakhlagh, and Cory Hill at JPL in MDL. 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. The NASA InVEST program selected HyTI in 2018 to fly in late 2022 or later as part of its CubeSat Launch Initiative.

WIDE-BANDGAP MATERIALS

PHOTO-CATHODES

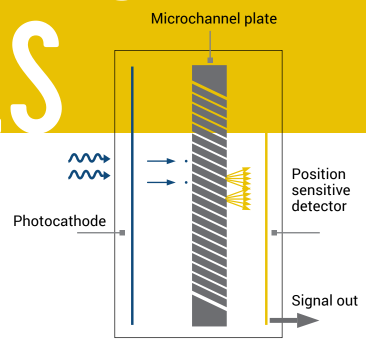


Fig.1: Simplified MCP detectors system.

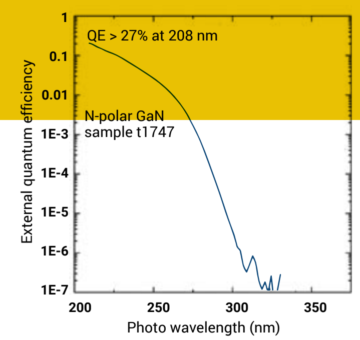


Fig.2 Visible/UV emission for a non-cesiated N-polar p-GaN photocathode. Data is plotted as external quantum efficiency (electrons out per photon incident). High values of QE in the UV have been demonstrated.

Atmospheric detection and composition studies, as well as measurements of aurorae, are high priorities in planetary missions. Ultraviolet (UV) emissions reveal the chemistry and physics of the upper atmospheres of planets and of satellites with atmospheres, as well as the surface compositions of rocky bodies. UV spectra have provided key information on the Io plasma torus, identified water vapor in the plumes of Enceladus, and revealed plumes from Europa. Additionally, some of these missions would perform in high-radiation environments, for which the proposed technology's radiation tolerance would be well suited.

UV measurements for astrophysics, planetary, and heliophysics missions during the next two decades will require significant detector advances, particularly in quantum efficiency, resolution, and pixel count. A critical feature of UV measurements is that a faint UV signal must often be detected over a background of substantial unwanted visible light. There are two possible solutions to this problem: photocathodes and solid-state detectors. Both are being pursued at MDL. They are based on gallium nitride materials and are described in more detail below.

UV detectors based on III-nitride offer significant advantages over current technologies. They provide intrinsic visible blindness and high temperature operations due to the wide bandgaps of the materials. Thus, for many applications, filtering is not required, providing wideband UV detection with strong long-wavelength suppression. The devices are capable of operating at higher radiation levels than those with silicon due to the greater strength of the Ga-N bond; this hardiness more readily allows operation in extreme environments. In addition, by alloying with Al, the Ga(Al)N family also offers tunability of properties to match the application. These features make GaN devices promising candidates for UV photon counting applications, both for astrophysics and planetary measurements.

Currently, photoemissive devices coupled with microchannel plates (MCPs) or electron-bombarded charge-coupled devices (and more recently electron-bombarded complementary metal oxide semiconductors) are used extensively in ultraviolet (UV) instruments. These detectors utilize a semiconductor photocathode (PC) to convert photons into electrons that are ejected into a vacuum and are subsequently amplified by the MCP (Fig.1).

Detection system performance critically depends on the efficiency and stability of the PC. In particular, PC instability and low quantum efficiency (QE) are responsible for many of the fabrication difficulties and performance deficiencies commonly experienced with this class of detectors.

We are developing PCs at MDL for UV measurements; they are based on the gallium nitride (GaN) materials family. GaN has important advantages as a PC material:

1) wide bandgap, therefore intrinsically blind to longer wavelengths.
2) physically and chemically robust, providing superior tolerance to damaging radiation.
3) tunable bandgap (and thus long wave-length cutoff) via alloying with Al or In.
4) low reactivity in air.

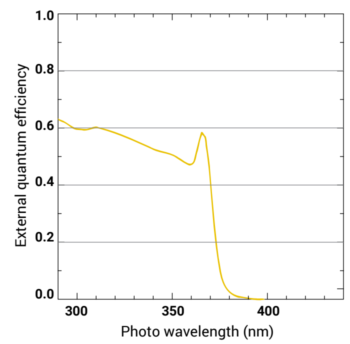
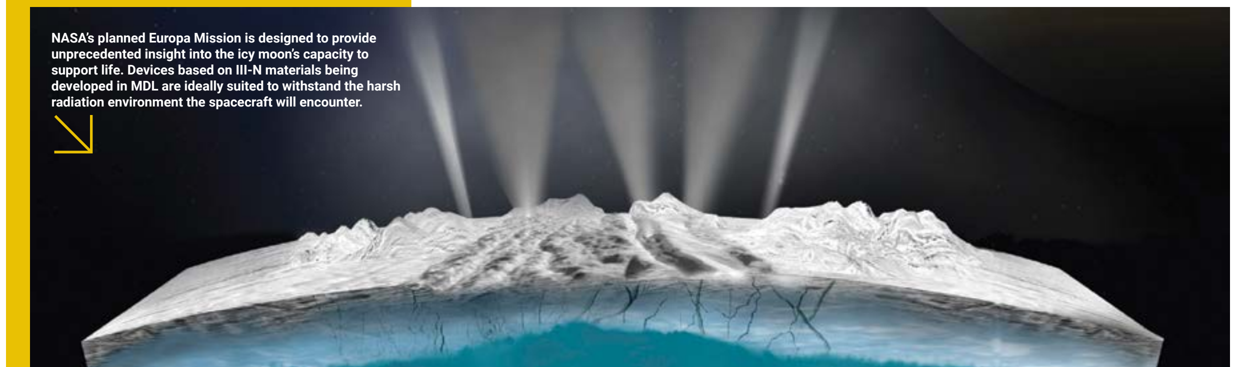
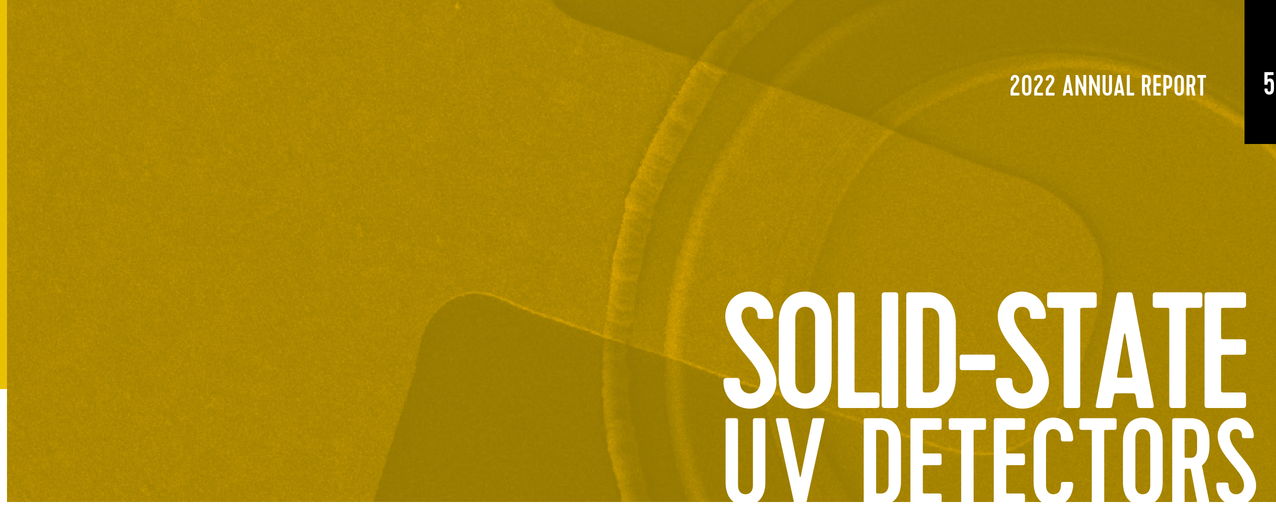


Fig.3 External quantum efficiency (electrons out/ photons incident) as a function of photon wave-length for a GaN *p-i-n* APD with zero applied voltage. High QE values have measured in III-N APDs.



NASA's planned Europa Mission is designed to provide unprecedented insight into the icy moon's capacity to support life. Devices based on III-N materials being developed in MDL are ideally suited to withstand the harsh radiation environment the spacecraft will encounter.



Scanning electron microscopy (SEM) image of a single-pixel GaN APD mesa structure with electrical contact.

To increase QE, low electron affinity is required, which reduces the energy required for photoelectron emission. Most PCs are vulnerable to degradation in air because low-electron-affinity materials are generally highly reactive with oxygen or water. We are investigating GaN PCs that can survive air exposure and exhibit high QE and robustness. By utilizing polarization charge in Ga(Al)N, as well as doping enhancement into semipolar crystal planes, we can obtain high QE without needing to treat the surface with reactive, low-electron-affinity materials such as cesium.

Figure 2 shows the response of a cesium-free GaN PC. QE is high in the UV, and rejection of longer wavelengths is many orders of magnitude; if higher rejection is desired, filters can be employed.

We are also investigating extrinsic surface layers to improve the lifetimes of these devices. The goal is to provide chemical protection for the PC surface layer while maintaining high photoelectron emission. We are evaluating 2D materials such as graphene and hexagonal boron nitride. These materials are impermeable to contamination, but because they are only a monolayer in thickness, high electron transmission should still be obtainable. We are currently optimizing deposition and surface treatment methods to demonstrate the applicability of 2D materials to UV PCs.

During the past year, MDL has made substantial progress on the QE of these devices, and we have now achieved over 30% QE for GaN PCs, a remarkable efficiency for non-cesiated devices.

These PCs can survive air exposure without permanent degradation in performance. Current work will improve stability over time by investigating protective surface monolayers, such as graphene, that will preserve electron emission while protecting the surface from reactions with the environment. For GaN avalanche photodiodes, MDL is studying a novel detector structure that provides dynamic wavelength-tunability of the device's response to light, integrated with the APD's high internal gain.

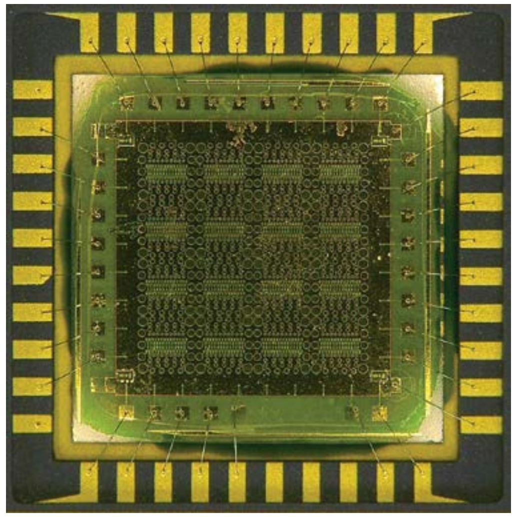
JPL is teaming with the SUNY Polytechnic Institute to develop these devices. Prof. Shahedipour-Sandvik's group is a leader in III-nitride growth and device development. JPL has worked with four graduate students who have based their thesis work on this collaboration. The collaboration with SUNY began over ten years ago and was motivated by NASA's need for radiation-tolerant, low-power, high-QE UV detectors, as well as SUNY's expertise in the growth of GaN materials. The work is funded by NASA's Astrophysics Research and Analysis (APRA) program.

SOLID-STATE UV DETECTORS

VERY-HIGH-GAIN DETECTORS THAT ALSO REJECT LONG WAVELENGTHS

Solid-state UV detectors are being developed using the GaN family of materials. Avalanche photodiodes (APDs) are heterostructure devices that allow photon counting by producing large internal gain. UV light is absorbed, creating electron-hole pairs. These carriers enter a multiplication layer where a large applied voltage (~100 V) produces avalanche multiplication. APDs are a well-studied class of high-gain devices, producing gains of 104-105. By fabricating these devices from Ga(Al)N, we obtain intrinsic long-wavelength rejection, as well as the ability to tailor spectral response by optimizing the Al alloy fraction in the photon absorption region.

High QE (Fig.3) and high avalanche gains (>105) have already been demonstrated for GaN APDs. Pixel arrays have been fabricated, and dedicated readouts have been designed and fabricated to accommodate the bias voltages required for avalanche operation.



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

c-FIRST

A SPACEBORNE INSTRUMENT TO OBSERVE AND QUANTIFY THERMAL EMISSIONS FROM FIRES AND VOLCANOES

The Compact Fire Infrared Radiance Spectral Tracker (c-FIRST) is a modular high-dynamic-range (HDR) multispectral imager with the flexibility to operate in the short-, mid- or long-wavelength infrared (IR) spectral bands for the remote sensing of high-temperature targets, including fire on the Earth's surface.

The remote sensing and characterization of these types of targets is important in many cross-disciplinary science investigations and applications, including the effects of fire and volcanoes on ecology, the carbon cycle, and atmospheric composition. For decades, this type of research has been hindered by insufficient spatial resolution and/or detector saturation of satellite sensors operating at short- and mid-IR wavelengths (1-5 µm), where the spectral radiance from high-temperature (>800 K) surfaces is most significant.

To address this critical need, JPL, in collaboration with partner institutions, is developing a compact modular HDR multispectral imager with the flexibility to operate in the short-, mid- or long-wavelength IR spectral bands. The goal of this NASA Instrument Incubator Program (IIP) project is to demonstrate this novel technology through the maturation of a mid-wavelength IR (MWIR) imager, the Compact Fire Infrared Radiance Spectral Tracker (c-FIRST), which leverages digital focal plane array (DFPA) developments from the NASA Advanced Component Technology (ACT) Program.

The DFPA is hybridized from a state-of-the-art high operating temperature barrier infrared detector (HOT-BIRD) and a digital readout integrated circuit (D-ROIC), which features an in-pixel digital counter to prevent current saturation; it thereby provides a very high dynamic range (>100 dB). The DFPA will thus enable unsaturated, high-resolution imaging and quantitative retrievals of targets with a large variation in temperatures, ranging from 300 K (background) to >1600 K (hot flaming fires). With the resolution to resolve 50-m-scale thermal features on the Earth's surface from a nominal orbital altitude of 400 km, the full temperature and area distribution of fires and active volcanic eruptions and the cool background will be captured in a single observation, increasing the scientific content per returned byte. The use of a non-saturating detector is novel, overcomes previous problems where high radiance values saturate detectors (which diminishes the scientific content and usefulness of the data), and demonstrates a breakthrough capability in remote sensing — one with broad applicability in both terrestrial and planetary settings.

By incorporating this technology, c-FIRST is suitable for quantifying emissions from fires and volcanic eruptions of different temperatures and intensities, which is critical for establishing their impact on ecosystems, carbon fluxes, and air quality at local scales and climate at global scales. c-FIRST will incorporate artificial intelligence (AI) approaches to identify events of high scientific value (e.g., wildfires and volcanic eruptions) while limiting the need for significant onboard storage or high bandwidths for data downlink, which is a particular handicap for high-spatial-resolution satellite sensors.

An image of a 1280x480 pixel mid-wavelength digital focal plane array on a ceramic chip carrier. Ceramic chip carrier is mounted on to a daughter board with proximity electronics.

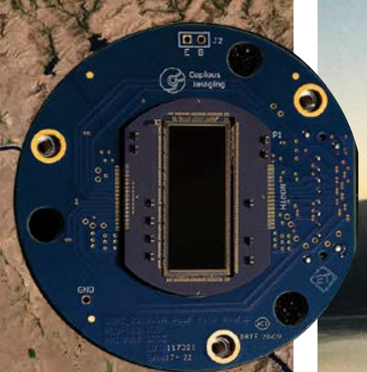
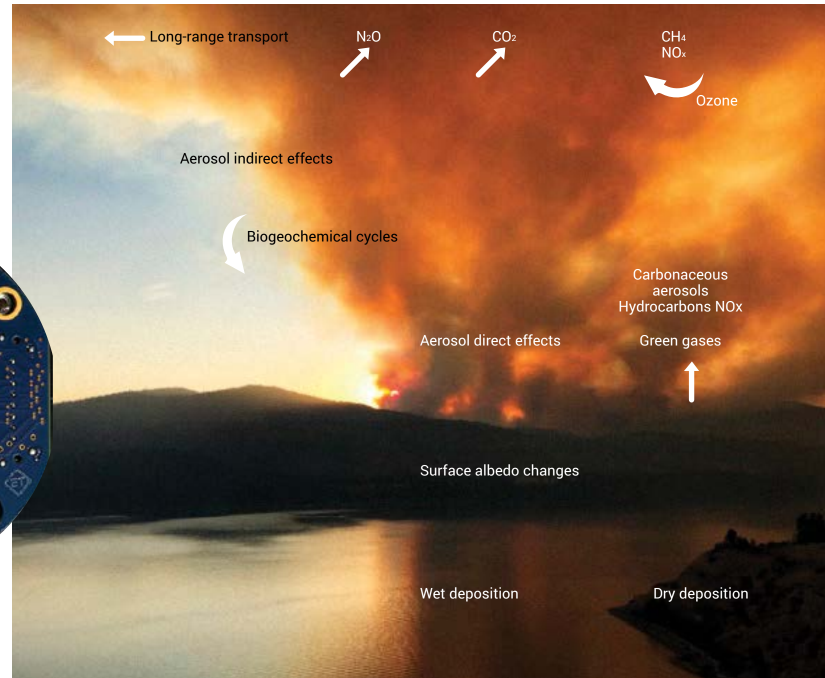


Figure adapted from Ward et al. (2012). Williams Flats Fire 2019. Photo credit: David Giles.



When deployed in a future constellation (not proposed as part of this work), multiple instruments could communicate directly with one another to perform continuous tracking and focused quantitative characterization of the thermal emissions from fires and volcanoes. This modular, AI-enhanced instrument design will enable and accelerate the development of constellations of intelligent, interacting CubeSats or SmallSats.

In addition to detecting fires from space, c-FIRST will obtain information about a fire's combustion temperature, which affects the emissions, propagation, and physical threat of the fire. Accurate estimations of the emissions from burning biomass are currently limited by a lack of knowledge about the fire burning phase.

c-FIRST will be developed to provide data on a fire's radiative power, brightness, temperature, location, size, and emissions from burning biomass. Improving observationally based biomass burning emission inventories in climate and air quality forecast models is directly related to the science question, "Are carbon sinks stable, are they changing, and why?" and the related objectives "quantify the flow of carbon in terrestrial ecosystems" (E-3a), "discover cascading perturbations in ecosystems related to carbon storage" (E-5b), and "understand ecosystem response to fire events" (E-5c) in the 2017-2027 Decadal Survey for Earth Science and Applications from Space.

The c-FIRST project was selected by NASA's IIP-21 program, which was established to provide technology developments for instruments and instrument subsystems that will enable future Earth science measurements and visionary Earth observing concepts.

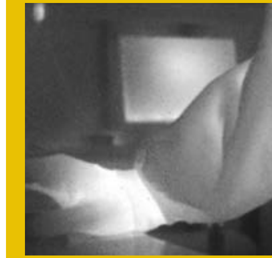
The instrument is being developed by Drs. Sarath Gunapala, David Ting, William Johnson, Alexander Soibel, Olga Kalashnikova, Michael Garay, Ashly Davies, Brian Pepper, Arezou Khoshakhlagh, Sir (Don) Rafol, and Cory Hill at JPL. The project is run in collaboration with Copious Imaging, Magnolia Optical Technologies, the University of Iowa, the University of Utah, the Naval Research Laboratory, and NOAA.

INFRARED IMAGING FOCAL PLANE ARRAYS

HIGHER OPERATING TEMPERATURE DETECTORS WITH EXCELLENT TEMPORAL STABILITY

III-V semiconductor thermal infrared (long-wave IR) imaging focal plane arrays (FPAs) are known for their high operability, spatial uniformity, temporal stability, and affordability. In recent years, NASA has successfully deployed III-V semiconductor-based long-wavelength quantum well infrared photodetector (QWIP) FPAs with a spectral response up to ~12 µm for land imaging applications, including the multispectral IR imager in the Landsat-8 Thermal Infrared Sensor (TIRS) instrument and the hyperspectral IR imager in the Hyperspectral Thermal Emission Spectrometer (HyTES) instrument. In both cases, the QWIP FPAs have demonstrated excellent temporal stability (low 1/f noise), which obviates the need for frequent system recalibration. QWIP FPAs require low operating temperatures because of their relatively high dark current and low conversion quantum efficiency (QE); the TIRS FPAs operate at ~43 K, and the HyTES FPA operates at ~40 K. It would be beneficial to explore alternatives to achieve higher FPA operating temperatures and reduced cryocooler demands while retaining the salient features of III-V semiconductor FPAs.

With the support of the NASA Earth Science and Technology Office (ESTO), we have taken advantage of recent advances in type-II superlattice (T2SL) infrared absorbers in combination with the unipolar barrier infrared detector device architecture to develop higher operating temperature long-wavelength IR (LWIR) detectors and FPAs for potential NASA sustainable land imaging (SLI) applications. Using JPL patented InAs/InAsSb T2SL complementary barrier infrared detector (CBIRD) technology, we demonstrated LWIR FPAs operating in the 60 – 69 K range with excellent uniformity and operability. With an industrial collaborator, we also demonstrated large-format LWIR InAs/InAsSb T2SL CBIRD imaging arrays using a silicon-on-silicon FPA technology, which opens the possibility of delivering high-performance multi-megapixel LWIR FPAs for future land imaging applications.



Infrared image taken with a 12.6 µm cutoff 640×512 format FPA operating at 65 K (top) and with a 11.3 µm cutoff 1280×1024 format silicon-on-silicon FPA operating at 80 K (above).

Mechanical layout of the HyTES instrument.

THz SPECTROMETER BASED ON VOLUMETRIC METAOPTICS

INVERTING THE DESIGN PROCESS PROMISES A NEW CLASS OF DEVICES

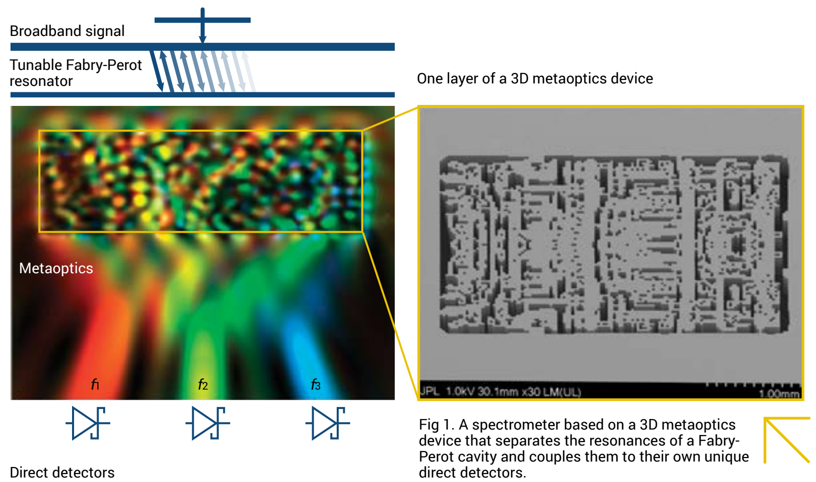


Fig 1. A spectrometer based on a 3D metaoptics device that separates the resonances of a Fabry-Perot cavity and couples them to their own unique direct detectors.

Much like a fingerprint, the spectra of atoms and molecules are their unique identifiers. Across the electromagnetic spectrum, molecules absorb and emit electromagnetic radiation at very specific wavelengths. Not only does this uniquely identify the molecule, it also offers insight into properties like abundance and speed of movement.

The tool behind these observations is the spectrometer, but using spectroscopy to investigate clouds on Venus and in distant galaxies is a major technical challenge. Using algorithms developed at Caltech, MDL is developing a new class of compact spectrometers that use stacks of patterned silicon wafers to separate different spectral lines to their own unique detectors. While most spectrometers are made of a modular arrangement of basic components like lenses and gratings, this spectrometer combines the functionality of many different components into a single block of patterned silicon that can be machined with extreme precision at MDL. The key to understanding what the device should look like is inverse design.

While many systems are designed by combining components with well-understood outputs, inverse design seeks to find a device that does exactly what the designer wants it do. The results are often non-intuitive, perhaps even random. Yet in reality, the shape of the device has been guided through hundreds of iterations of physics simulations and optimization to arrive at a solution. The non-intuitive shape simply comes from allowing physics, rather than human intuition, to lead the way, and the subwavelength features that imbue the device with its interesting properties also lend the name metaoptics to this type of device.

The device shown is made of stacked silicon wafers and simultaneously separates colors, like a grating or prism would, while also focusing the colors onto their own detectors. The whole process occurs using a cube that is only a few wavelengths to a side. The result is the ability to scan a broader range of frequencies and a substantial reduction in the number of required components, which ultimately improves the volume, mass, and overall efficiency of the spectrometer.

THz QUANTUM-CASCADE LASERS

NEW, COMPACT FLIGHT INSTRUMENTS PROBE THE SECRETS OF THE BIRTH OF STARS

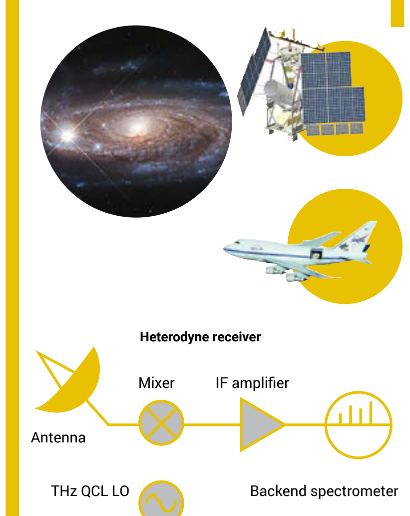


Fig 1. THz heterodyne detectors are used to observe the lifecycle of the interstellar medium. THz QCLs are needed as local oscillators.

New stars form in interstellar gas clouds (Fig. 1). The compositional details and dynamics of this gas can be investigated using very long wave spectroscopy, greater than 50 µm or 6 terahertz (THz). However, local-oscillators (LOs) for heterodyne detectors that have sufficient spectral resolution for detailed observations have been limited by the efficiency of existing electronic LO sources (primarily diode multipliers), which fall off strongly above 1-2 THz. While other sources of coherent THz radiation, such as molecular gas lasers, have been available at JPL, they are large benchtop sources that are impractical for space- or balloon-based instruments.

During 2021, MDL developed a process for fabricating THz quantum-cascade lasers (QCLs) in its cleanroom. THz QCLs are the longest wavelength semiconductor lasers that have been demonstrated to date, typically operating between 50 – 200 µm, or 3 -6 THz. These THz QCLs will act as LOs for heterodyne detectors that have sufficient spectral resolution to resolve Doppler broadened emission lines, allowing for 3D kinematic mapping of galactic structures within the Milky Way. Our newly developed in-house THz QCL production can extend JPL's capabilities higher into the THz frequency range. THz QCLs are very compact sources that can still provide milliwatt power levels, but they operate at cryogenic temperatures (typically <100 K), so the size, weight, and power (SWaP) of a THz QCL source is largely limited by the required cryocooler. Current work seeks to demonstrate devices with >1 mW of THz power using a cryocooler dissipating <30 W.

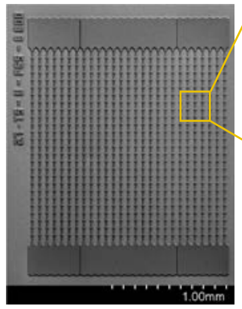
Since they were first demonstrated in 2002, THz QCLs have been considered for their potential to enable THz heterodyne instruments, but they have suffered from poor beam quality and limited frequency tunability, making it difficult to build practical instruments.

MDL is fabricating a new type of surface-emitting, external-cavity THz QCL that can provide excellent beam quality and >10% fractional frequency tuning. This type of laser design, termed a vertical-external-cavity surface-emitting laser (VECSEL), was first demonstrated with THz QCLs in 2015 at UCLA [1]. MDL is now developing this technology with a focus on meeting the metrology standards and SWaP limitations necessary for future balloon- and/or space-based instruments.

The QC-VECSEL consists of a surface-coupled QC-based THz amplifier, which forms an oscillator when feedback is provided from an external, partially reflecting mirror. The lasing frequency of the VECSEL is determined by the length of the external cavity and can be tuned via piezoelectric control of the cavity length [2]. The QC-based THz amplifier essentially consists of an array of microstrip patch antennae that are loaded with THz QC-gain material. Scanning electron microscope (SEM) images of fabricated devices are shown in Fig. 2(a), and the frequency tunable VECSEL cavity is shown in Fig. 2(b) and (c). The molecular beam epitaxy (MBE)-grown THz gain material is obtained from a commercial vendor, and the material is processed into THz amplifiers at MDL. Devices have currently been fabricated at 2.7 THz and 4.7 THz, which are aligned with key astrophysical targets of hydrogen deuteride (HD) and neutral oxygen (OI). In addition to acting as a LO source, the THz amplifier component of the QC-VECSEL can potentially be used independently as a front-end amplifier for heterodyne detectors, improving the sensitivity of such detectors by a factor of 2 – 10. This could provide an important breakthrough in improving the sensitivity of THz heterodyne detectors, which has otherwise plateaued at ~5× the quantum limit for the last 20-30 years. Funding opportunities for such amplifier work are currently being pursued.

[1] L. Y. Xu, C. A. Curwen, P. W. C. Hon, Q. S. Chen, T. Itoh, and B. S. Williams, "Metasurface external cavity laser," Appl Phys Lett vol. 107, (2015).

[2] C. A. Curwen, J. L. Reno, and B. S. Williams, "Broadband continuous single-mode tuning of a short-cavity quantum-cascade VECSEL," Nat Photonics vol. 13, 855-859 (2019).



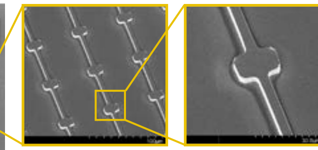


Fig 2 (a)SEM images of a fabricated THz QC-amplifier.

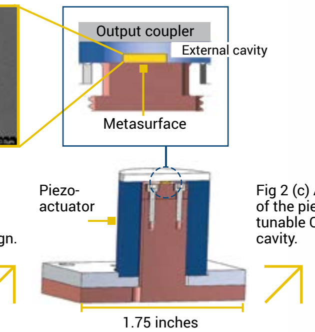


Fig 2 (b) An illustration of the tunable QC-VECSEL design.

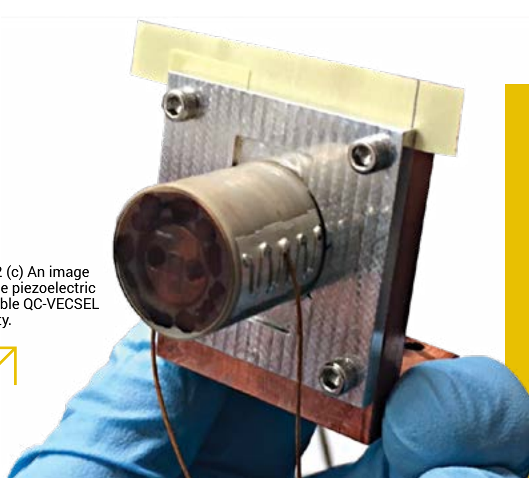
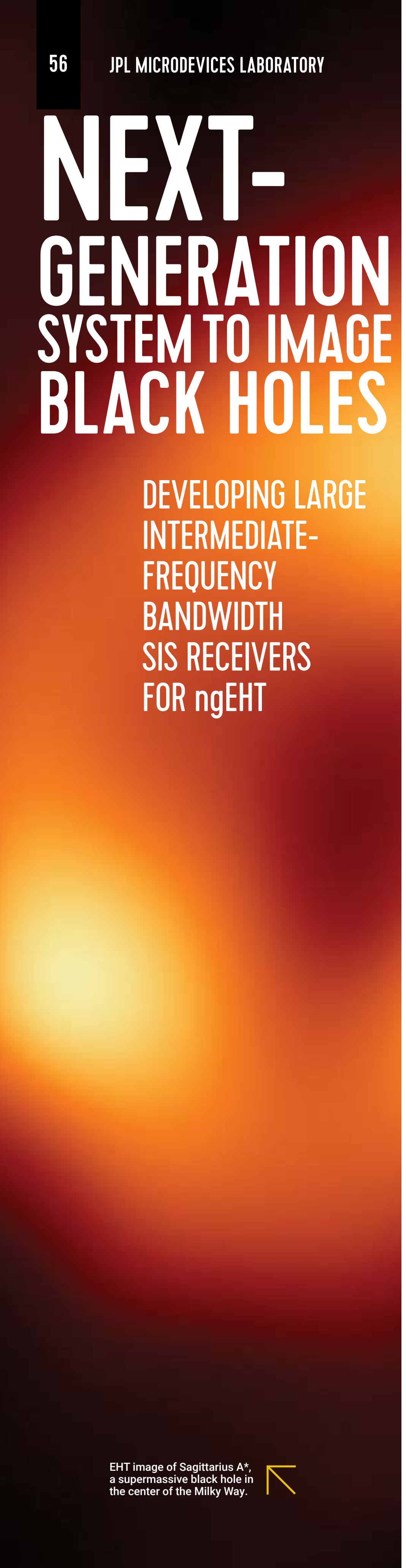


Fig 2 (c) An image of the piezoelectric tunable QC-VECSEL cavity.



NEXT-GENERATION SYSTEM TO IMAGE BLACK HOLES

DEVELOPING LARGE INTERMEDIATE-FREQUENCY BANDWIDTH SIS RECEIVERS FOR ngEHT

EHT image of Sagittarius A*, a supermassive black hole in the center of the Milky Way.

A global research team called the Event Horizon Telescope (EHT) Collaboration uses observations from a worldwide network of radio telescopes and recently produced the first image of the black hole at the center of our galaxy. The EHT operates superconducting insulator superconducting (SIS) receivers in the 230 gigahertz (GHz) band with an effective 5-11 GHz intermediate frequency (IF) bandwidth. Though excellent, there is a need to enhance the angular resolution of the (global) interferometric imaging array with state-of-the-art 345-GHz SIS receivers operating in the 275 – 373 GHz frequency range (ALMA Observatory Band 7 receiver). To further increase the interferometer sensitivity to continuum (dust) emission, it is desirable to extend the IF bandwidth to 20 GHz, a practical upper limit for low noise amplifiers with input referred noise levels of <= 10 K. MDL is contracted to develop this new set of SIS mixers (Fig. 1) for the next-generation Event Horizon Telescope (ngEHT), under contract to Caltech and the Harvard Smithsonian with funds from a Major Research Instrumentation (MRI) research grant from the National Science Foundation. It is envisioned that in the long-term, baselines will be extended beyond the Earth perimeter into space, henceforth involving NASA activity.

The SIS mixers under development are based on 8 µm silicon on insulator (SOI) with a 1 µm oxide (BOX) layer and 300 µm handle layer. They are arrayed in a 2 x 8 frame providing up to 16 devices per 8 mm frame, as depicted in Fig. 2a.

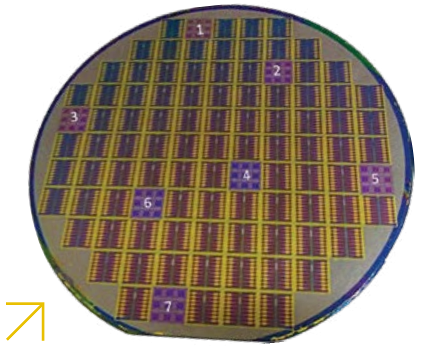
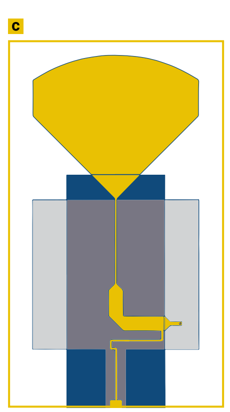


Fig1. SOI wafer with ~ 80 frames; each frame consists of 2 x 8 sets of 345 GHz SIS devices.

The advantages of this novel approach are 1) ease of handling and 2) uniformity within the frame. The latter is very important, as the SIS mixers are used in sideband separating (2SB) configuration. Additionally, 3) the frames are registered by a row-column (RC) number with the devices themselves labeled as junctions 1-16. This approach allows for the unique identification and tracking of devices across the wafer, again important in identifying high-quality uniform devices. Finally, 4) with the frame concept design, variations can be introduced (in our case three) to account for R_nA product (current density) fabrication tolerances.

The actual SIS tunnel junctions (Fig. 2a, b) have an AlN barrier and consist of an Nb top and bottom electrode. Utilizing AlN as the barrier affords a nominal current density of 8/Ω µm², which has an omega*R*C = 1 product of ~ 240 GHz where omega is 2*pi*frequency. Extensive software simulations with Sonnet em and HFSS Comment end packages show that the junctions supports IF frequencies in excess of 20 GHz. To measure the mixer performance (RF and IF), MDL has procured two double sideband mixer blocks and relevant IF hardware. The deliverable to the Harvard Smithsonian Center for Astrophysics (CFA) is the equivalent of one wafer, or ~ 70-80 frames.



Magnification 500X

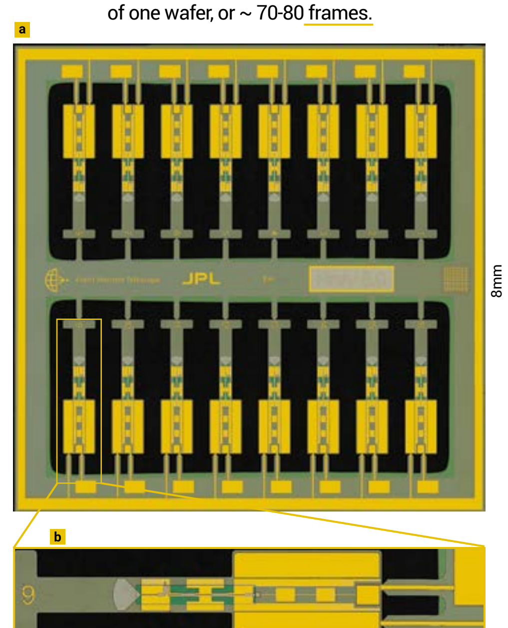
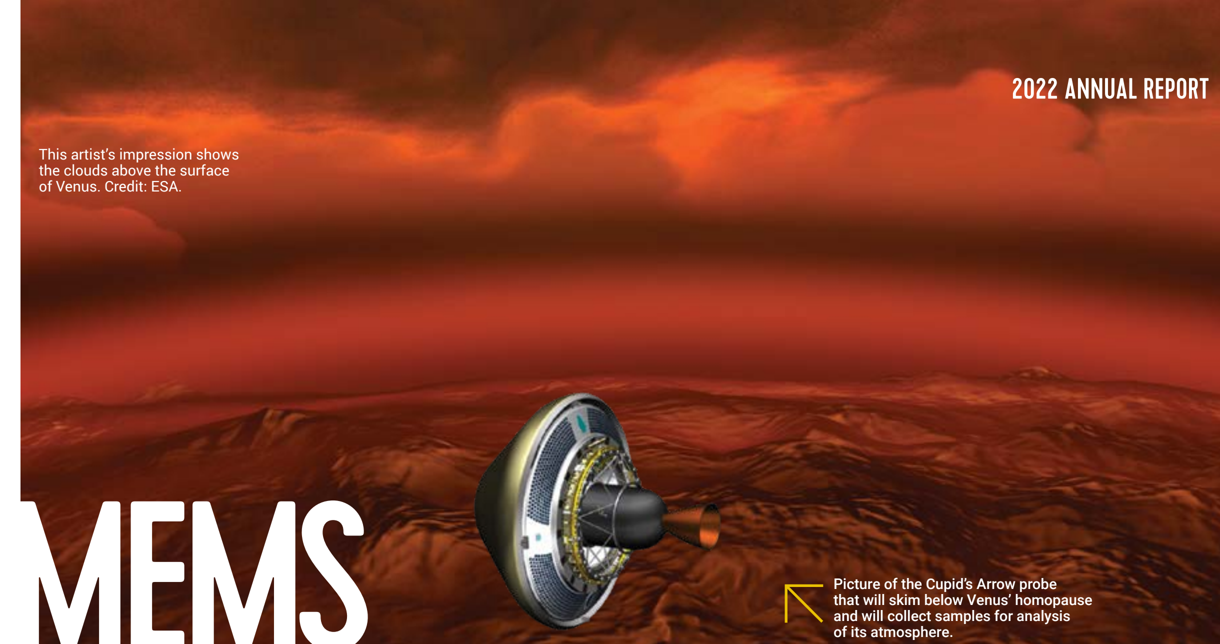


Fig 2. **a**. Silicon frame with 16 SIS devices. **b**. Close up of a single device. IFs with a 1 dB conversion loss are supported to 20 GHz. **c**. 1.6 µm single SIS junction with the waveguide to thin film microstrip transition. The design incorporates two SIO_2 dielectric layers: 250 nm and 450 nm, with the 250 nm thickness being used in the junction area.



This artist's impression shows the clouds above the surface of Venus. Credit: ESA.

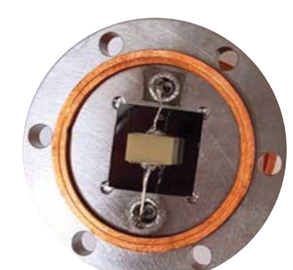
Picture of the Cupid's Arrow probe that will skim below Venus' homopause and will collect samples for analysis of its atmosphere.

MEMS PIEZOELECTRIC VALVE

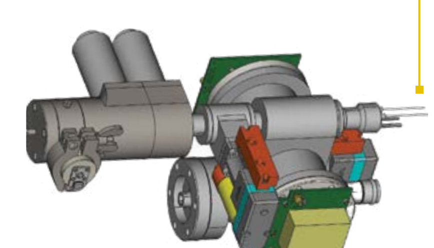
FOR AEROSOL SEPARATOR INLET TO THE VENUS AEROSOL MASS SPECTROMETER

The inner planets all have similarities and very significant differences. By studying them, we will learn how Earth developed as it did and became habitable. Consequently, the 2013 Decadal Survey recommended two New Frontiers missions with enhanced funding, and one of the prioritized possibilities was an *in situ* investigation of the surface of Venus. Because of Venus' thick cloud cover, its remote observation is almost impossible. Its very high surface temperature and its clouds, which are composed of sulfuric acid droplets, make it a challenging target for *in situ* exploration. Any mission would want to analyze the amounts and isotopic compositions of as many species as possible in the atmosphere. Another challenge is the very high atmospheric pressure, which is more than 90 times that of Earth's at the planet's surface.

Foreseeing the possibility of such New Frontiers proposals, JPL made internal investments through the Center Innovation Fund and Spontaneous Research & Technology Development (R&TD) awards to strengthen the case for selecting the JPL quadrupole ion trap miniature mass spectrometer. The prerequisite was that the mass spectrometer should be able to take in atmospheric samples for analysis.



Top view of the microvalve in a custom housing with ConFlat® (CF) gasket.



The Venus Aerosol Mass Spectrometer.

However, the analyses require the intake of gases and aerosols at optimal pressures controlled by a microelectro-mechanical systems (MEMS) piezoelectric valve. The sample is introduced into an aerosol separator that separates aerosols from the resident gas, with the pressure measured by a Micro Pirani gauge.

The piezo valve consists of a Rogers electrical feedthrough with the air side featuring a silica seat wafer bonded to the actuator membrane and the ceramic actuator with silver epoxy electrical contacts. Applying voltage to the actuator, will induce the stroke that lifts the membrane off the seat wafer and opens the valve to the flow of aerosol-laden gas. The flow rate will be monitored by the Micro Pirani gauge and adjusted by changing the applied actuator voltage, enabling stable gas flow into the mass spectrometer regardless of changes in the outside pressure.

MEMS piezoelectric valves with 5 µm actuators were already developed for gas flow regulation at inlet pressures of up to 60 bar. Modifications to transmit aerosol-laden gas consisted of a new valve membrane design, new seat wafer etching, and a design to support actuators with 7 µm and 10 µm strokes. Progress has been excellent: two 5 µm valves are being finalized, and actuators are to be bonded to the rectangular membrane and flow-improved seat wafers. Flow-improved circular membranes (12 pieces) and seat wafers (8 pieces) have been fabricated. The 7 µm and 10 µm actuators have been delivered and will be bonded with the membranes and seat wafers.

VISIBLE-BAND FREQUENCY COMBS FOR EXOPLANET EXPLORATION

Once this device has been packaged, the team plans to perform optical characterization using the Keck Planet Finder, a precision radial velocity instrument designed for the Keck Observatory in Hawaii (shown).

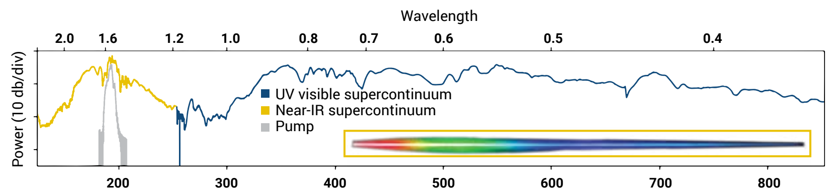
REDUCING THE SIZE OF A COMPONENT BY TWO ORDERS OF MAGNITUDE WHILE IMPROVING ITS PERFORMANCE

Both the National Academies 2020 Decadal Survey on Astronomy and Astrophysics and the 2022 NASA Strategic Plan identify the search for habitable Earth analogs beyond our solar system as a key objective for space science. A very powerful tool in this search is the ability to measure precision radial velocity (PRV) in extrasolar systems. The PRV technique analyzes the reflex motion of a star in response to an orbiting planet by tracking the frequency shift of lines in the stellar spectrum, ultimately revealing the mass and orbital dynamics of an exoplanet. An essential ingredient of PRV instruments is a stable, reliable frequency reference for spectral calibration. An MDL effort is underway to address this need by building a next-generation PRV spectrograph calibrator.

Because laser frequency combs produce evenly spaced spectral lines and can be locked to an absolute reference, they are useful as high-stability frequency rulers. The most mature laser frequency combs currently function at near-infrared wavelengths; however, solar-type stars have most of their spectral content concentrated at shorter visible wavelengths from 400 to 800 nm, making this band ideal for PRV measurements. Furthermore, the ideal comb line spacing for PRV spectrographs is 10 to 20 GHz in frequency, corresponding to about 0.01 to 0.02 nm at a 600-nm wavelength. To leverage near-infrared technologies while providing comb lines in the visible band, the team is using wavelength conversion in nonlinear photonic waveguides that are pumped with a high-repetition-rate (≥10 GHz) near-infrared electro-optic comb. The nonlinear waveguides are fabricated on thin-film periodically poled lithium niobate-on-insulator (PPLNOI) chips. These centimeter-scale devices can be packaged in compact, robust enclosures and replace the functionality of meter-scale rack-mounted state-of-the-art visible combs based on unreliable nonlinear optical fibers and free-space optical filters.

To date, the team has designed, fabricated, and demonstrated a PPLNOI device pumped with a narrowband near-infrared comb to generate a spectrum spanning more than two octaves, from 350 to 2000 nm. This device features a dispersion engineered waveguide with a chirped poling period that exploits both second- and third-order optical nonlinearity in the lithium niobate. The team aims to have a device packaged and ready for testing with an observatory-based PRV instrument in the second half of 2022. This work was performed with the University of Colorado, Boulder and Caltech.

An image of the thin-film lithium niobate device during testing.



Emission from a near-infrared laser frequency comb (gray) and measured emission after passing through the periodically poled thin-film lithium niobate waveguide designed for this project to create a visible-band comb. The inset shows a photograph of the visible light emitted from the waveguide after being dispersed on a grating.

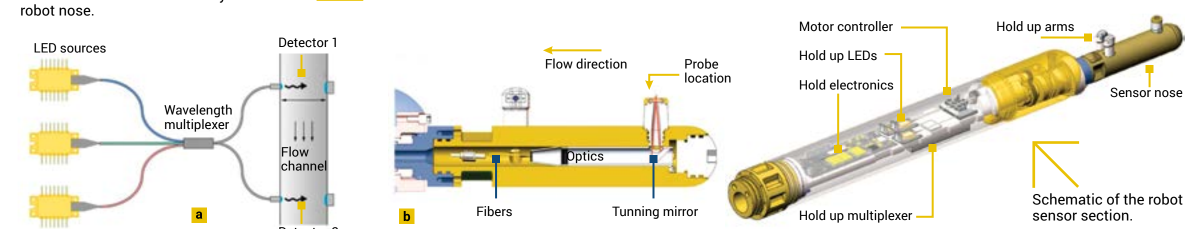
NOVEL SENSORS FOR OIL WELL CHARACTERIZATION

MEASURING THE VELOCITY OF A FLUID, AN IMAGINATIVE LATERAL APPLICATION OF MDL TECHNOLOGY

Novel planetary science mission concepts rely on the development of sensors capable of making accurate measurements in harsh environments. For example, mission architectures focused on Enceladus plumes, including a concept under consideration for New Frontiers, as well as the Exobiology Extant Life Surveyor (EELS), will require detailed knowledge of velocities and mass flux of particles entrained in gas both for sample targeting and asset security. On Earth, sensors are needed to study harsh environments for a variety of applications. The characterization of multi-phase flows inside oil wells is of great importance for the oil and gas industry, as it provides crucial information about the state of the reservoirs. *In situ* measurements can distinguish areas of high productivity, guiding decisions for drilling new wells in high-value areas.

In a collaborative effort between Chevron, the JPL Extreme Environment Robotics group and the JPL Advanced Optical and Electro-Mechanical Microsystems group, MDL developed a suite of sensors capable of characterizing fluid streams in horizontal oil wells under elevated temperature, 80 °C, and pressure, up to 5,500 psi, aboard an autonomous robotic platform, the Below-ground Autonomous Data Gathering Robot (BADGR). To retrieve the oil sources along the oil well, MDL developed an LED-based composition sensor capable of measuring the presence of oil, supercritical methane, or water. A laser Doppler velocimeter (LDV) that measures the velocity where the flow composition is being measured has been developed in collaboration with Measurement Science Enterprise, a leader in the development of robust miniaturized LDV. This autonomous robot equipped with MDL sensors can move back and forth within the well and perform several measurements along the pipe. Using a rotating sensor head, each set of measurements gives the axial profile of the flow for a given location, allowing the retrieval of areas of high productivity and enabling the understanding of fundamental characteristics of oil wells. The autonomous robot has been tested in a realistic environment in collaboration with the Southwest Research Institute (SwRI). It has the potential to impact the development of future oil wells by only targeting high-productivity areas and minimizing environmental disturbances.

(a) Schematic drawing of the LED-based composition sensor capable of measuring the presence of oil, supercritical methane, or water. (b) Schematic drawing of the LDV that measures the flow velocity inside the robot nose.



Schematic of the robot sensor section.

MID-INFRARED COMB-ENABLED CAVITY-ENHANCED VERNIER SPECTROSCOPY

POTENTIAL FOR VERY FAST VERY SENSITIVE CHEMICAL SENSORS

Optical frequency combs (OFCs) enable broadband, high-resolution miniaturized laser spectrometers that can identify complex organic molecules and grant narrowband absorption features with potential applications ranging from atmospheric chemistry to geological science and the search for extraterrestrial life. Using chip-scale OFCs based on interband cascade lasers and a tunable high-finesse optical cavity, a Vernier spectrometer was demonstrated in which the optical cavity simultaneously enhances the sensitivity and selectively filters the individual comb lines. The Vernier spectrometer allows dynamic sensing with high temporal resolution. This prototype system shows the promise of future miniaturized cavity-enhanced spectrometers for chemical sensing. The prototype instrument does not exceed 3’x1’x1’in size and 4 kg in weight, and it consumes no more than several watts of electrical power. As a proof of concept, the broadband detection of a hydrocarbon (automotive refrigerant HFC-152a – 1,1,-difluoroethane [DFE]) in real time with a millisecond refresh rate was demonstrated. The achieved ppm-level sensitivity in milliseconds promises parts-per-billion limits of detection over timescales of a minute. This technique’s advantages include its compatibility with both free-running comb operation and cavity enhancement as compared to other spectroscopic techniques using OFCs. These two features allow for a relatively simple setup to reach high spectroscopic sensitivity. The work was a collaborative effort between teams at JPL, Caltech and the Naval Research labs.

LOW-NOISE LASERS OFFER NEW CAPABILITIES FOR RADAR

THE NEXT GENERATION OF RADIOFREQUENCY SOURCES MAKE LIGHT AND SOUND WAVES INTERACT

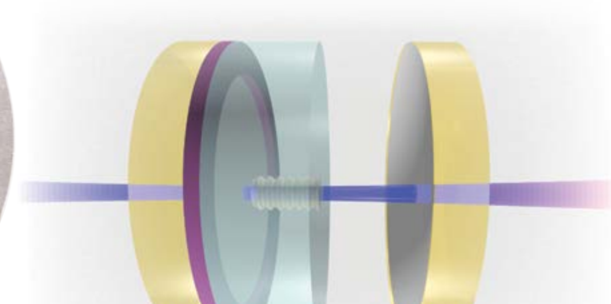
Artistic representation of the Brillouin laser, showing the interaction between light and sound in an opto-mechanical cavity.

Radar instruments have a long history of valuable scientific contributions, from mapping the surface of Venus with Magellan to probing of the Earth's atmosphere through missions such as CloudSat. Looking forward to future scientific goals, such as the global profiling of thermodynamic variables within the lower troposphere, space-based radars with unprecedented sensitivity will be required. Common to all radar instruments is a means to generate the transmitted radiofrequency (RF) signal. While this is typically achieved with frequency-multiplied electronic oscillators, the noise performance of all-electronic sources degrades rapidly at higher frequencies. As a result, alternative approaches are necessary to enable the next generation of low-noise microwave and millimeter-wave radars.

Counterintuitively, low-noise lasers provide a promising solution. Like RF electronics, laser oscillators involve electromagnetic radiation, albeit at far higher frequencies. Consequently, the low loss of optical components has allowed for several laser oscillator technologies with noise performance far exceeding that achieved with lossy electronic systems to be applied to this issue. Once two or more optical signals with such low noise are generated, they can be down-converted to the RF domain using a conventional semiconductor photodetector. As a result, flexible and low-noise signal generation ranging from gigahertz (GHz) to terahertz (THz) frequencies can in principle be achieved. However, there is often a tradeoff between size, complexity, and performance. While lab-scale optical experiments have created the lowest-noise oscillators and highest-precision clocks in existence, it is often nontrivial to translate these systems into robust field-deployable components. By contrast, integrated photonic lasers have been used to develop chip-scale microwave synthesizers, but performance is limited by power handling and fabrication imperfections.

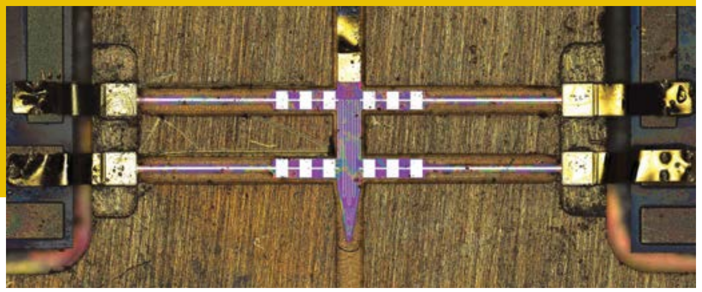
To advance the readiness of so-called "RF-photonic" technologies for space, MDL has developed an ultra-low-noise laser based on a compact opto-mechanical cavity. This device, developed in collaboration with Yale University, creates an ultra-low-noise laser based on interactions of light waves with high-frequency sound waves in a tiny piece of glass through a process known as stimulated Brillouin scattering. The internal physics of this process acts as a "noise eater". The resulting Brillouin laser generates laser light around a frequency of 194 THz with an instantaneous linewidth of 0.025 Hz. In terms of oscillator phase noise, this corresponds to a noise level of -125 dBc/Hz at 100 kHz offset. When mixed down to frequencies relevant for scientific radars in the ~100s of GHz range, this represents a decrease in transmitter noise, and hence an improvement in the measurement dynamic range, of 100x.

This performance level results from extremely low optical losses and parasitic effects in the laser cavity design. Because it uses bulk optical components, light scattering and absorption are minimized. At the same time, unwanted thermal and optical nonlinearities are practically eliminated. The entire laser cavity is housed in an inch-scale cube implementing fiber-optic coupling, as well as thermal and mechanical stabilization. Efforts are ongoing to prepare the device for field deployment and test in a 168 GHz radar. Looking forward, the photonic oscillator approach will likely improve the capabilities of future atmospheric radar instruments, such as JPL's Vapor In-Cloud Profiling Radar (VIPR), that will provide valuable climate-relevant measurements of meteorological variables. The Brillouin laser may also find use in a variety of optical sensing applications where its extremely narrow linewidth and bulk design can also be applied to low-noise signal generation across the visible and infrared bands of the electromagnetic spectrum.



End-on view of the Brillouin laser cavity.

TEMPERATURE PROGRAMMABLE CALIBRATION LOAD



A NOVEL APPROACH TO CALIBRATE MICROWAVE RADIOMETERS

Fig 1. Calibration load *in situ* in a WR 1.5 waveguide. The heat flow to the (OFHC) Cu block is via the four arms, and with the load heated to 200 °C, the DC input power requirement is 160 mW. The blocks are Au plated to minimize radiation loading. As expected, some radiation loading is evident above about 80 °C. Convective heat flow (air) has not been observed to be a problem. Eventual operation is via a ms programmable PID loop.

Radiometers employ a technique known as Dicke switching in which the radiometer beam is alternately switched between the observable source and a known calibration load. This process is typically done at a rate faster than or equal to the Allan variance stability time of the receiving system. At microwave frequencies, a known amplitude noise source signal can be injected via a 20-30 dB directional coupler in the front of the receiving system. At submillimeter or terahertz frequencies, this would be impossibly difficult, and as a result, the optical beam is usually mechanically switched between the source and the calibration loads. Needless to say, such a Dicke-switched calibration setup tends to be large, mechanically detailed, and prone to optical alignment and vignetting difficulties.

To overcome this problem, a novel 500-700 gigahertz (GHz) (WR 1.5 waveguide) calibration load has been developed that is temperature programmable on 6 μm silicon on insulator (SOI). As shown in Fig. 1, the calibration load consists of a heater, thermocouple, and a TiO_2 layer (not visible) with 230 Ω/surface resistivity.

The tapered profile and sheet resistance were optimized in high-frequency simulation software to provide a good match to the waveguide of the 500-700 GHz frequency band.

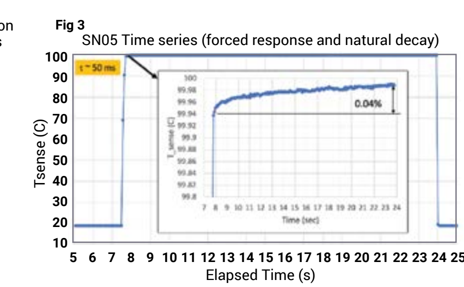
The heater and thermocouple sensor comprise an ~ 80 nm Al film with approximately 450 – 500 squares. The R-T behavior (Fig. 2) for both the thermal sensor and heater has been measured up to 250 °C and appears exceptionally linear.

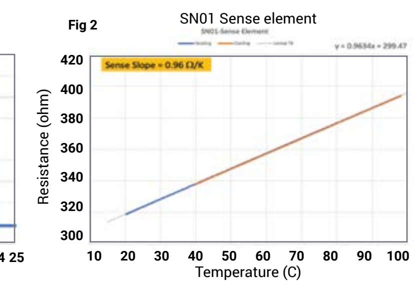
The calibration load works both at cryogenic and room temperatures up to ~ 250 °C (523 K). At room temperature (290 K – 533 K), the programmable noise is envisioned to be injected via a WR 1.5 microelectromechanical system (MEMs) switch (also developed at MDL). At cryogenic temperatures with more sensitive receivers, the programmable noise may be injected via a 10-20 dB directional coupler positioned at the receiver's front end. Results are preliminary, but it appears that above about 250 °C, the Al film will need to be annealed to stabilize the R-T curves. Below 240 °C, the curves are very repeatable and stable. Hence, the upper temperature of the calibration load is ~ 250 °C, although perhaps with a proper annealing procedure, this can be extended.

The time response of the calibration load is extremely fast, on the order of 50 ms for 1τ. In practice, the calibration load will need to be run of a dedicated ms time response proportional-integral-derivative (PID) controller whose temperature can be programmed to follow the characterized R-T curve. An added benefit of this approach is that for the first time, the linearity of receiving devices (Schottky mixers, monolithic microwave integrated circuits [MMICs], safety instrumented systems [SISs], etc.) can now be readily probed and characterized. Fig. 3 shows the time response to 100 °C. The response is so fast that the data acquisition software had to be re-written to (mostly) capture the rise time. With a steady-state voltage applied, there was a rise of 0.04% in the sense resistance temperature over a period of 24 seconds. The reason for this is the gradual heating of the WR 1.5 copper block over time. In actuality, with a PID loop control in place, the injected DC power would be throttled back to keep the sensor voltage constant. Notably, for more typical narrow-band applications, a tuning structure may be incorporated into the WR 1.5 input waveguide, thereby improving the RF match to ~ -30 dB. The design can easily be extended to lower or higher frequencies.

Fig 3. Measured time response of the novel calibration load. 3 τ ~ 150 ms to 100 °C with a steady-state bias applied. Under PID control, the forced time response may increase, as the loop will be set up to have a slightly overdamped response. The load will be operated between two non-ambient loads (like 40 °C and 240 °C), optimizing the time response.

Fig 2. Sensor R-T curve as measured in an (open to air) oven with the Cu block heated and cooled overnight to 100 °C.





MÖSSBAUER AND X-RAY FLUORESCENCE SPECTROMETER

A DUAL PURPOSE IN SITU ANALYTICAL INSTRUMENT

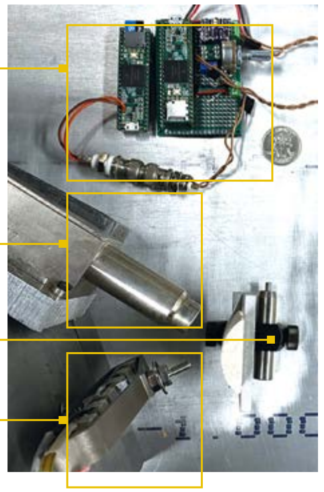
When exploring the surface of a planet and examining rocks, it is valuable to ascertain their chemical compositions. However, the atomic-scale arrangement of the chemical elements defines which mineral type is present; two different minerals may have the same chemical composition but very different properties. This information about atomic arrangement is essential for understanding the evolution of planetary bodies and is relevant in the search for life since certain minerals may have been produced by living organisms or be available to support them.

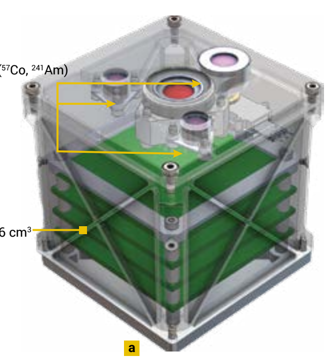
Various instruments can make either of these two critical measurements, and the two Mars Exploration Rovers launched in 2003 made such analyses. MDL, in collaboration with Professor Brent Fultz, Caltech, is leading the development of a miniature combination X-ray fluorescence (XRF) and Mössbauer spectrometer for chemical and mineralogical analyses, respectively. These routine geochemistry analyses are being combined into a single instrument package, targeting bulk material measurements on highly constrained platforms, such as the Cooperative Autonomous Distributed Robotic Exploration (CADRE) or future Mars helicopter concepts. Currently, NASA missions in need of either low size, mass, and power (SMaP) XRF or Mössbauer instruments must acquire individual instruments from foreign entities or build a custom instrument. Having flown by most of the solar system's terrestrial targets, there is a shift to landed missions, which are inherently mass constrained. By combining two techniques, this spectrometer will provide a low-SMaP option for key geochemistry instrumentation for future NASA missions. As NASA makes way for smaller-scale missions, readily available, low-SMaP instruments that deliver routine science will become more valuable. While the focus of the current development is the demonstration of a dual-mode instrument, these advances also allow for straightforward design modifications to generate standalone instruments, as well (e.g., standalone XRF).

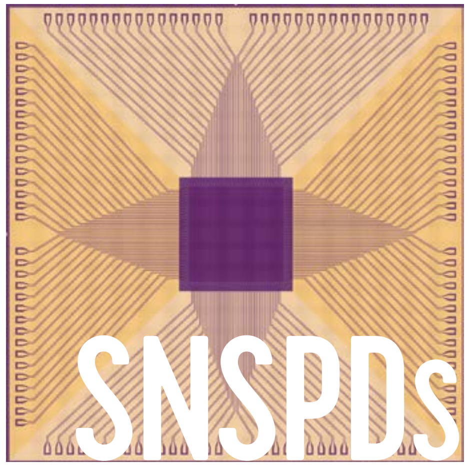
Traditional lab-based Mössbauer spectrometers utilize bulky electromagnetic Doppler drives to sweep the spectral window. To reduce the mass and power requirements on this functionality, a piezoelectric Doppler drive is being used instead. Preliminary proof-of-concept experiments using a bender actuator were successful, and moving to a flight-like piezo actuator design vastly improved the quality of the generated spectrum. Complete characterization of both piezoelectric Doppler drives using laser Doppler velocimetry will be conducted to understand the behavior of the drive and the spectrum generated, giving the team critical information to select a piezoelectric actuator for a given set of requirements (size, mass, and power) and have an idea of the science it will be capable of generating. Also key to the function of a miniature dual-mode instrument is in the ability to share critical hardware, namely the detector (silicon drift detector, or SDD), along with the photon counting and binning electronics. The team has now demonstrated the ability to simultaneously collect XRF and Mössbauer spectra using custom code and two Teensy microcontrollers, one for photon counting and binning of both spectra and one for actuator control and feedback. Detected photons are first binned using a multichannel analyzer mode (XRF), and peaks that fall within a specific energy range are added to the multichannel scalar mode (Mössbauer) and correlated with the wave driving the actuator. In parallel with this effort, the team is investigating specific components and flight boards that were developed for the Planetary Instrument for X-ray Lithochemistry (PIXL) mission and can be leveraged for this development, refining the path to higher technology readiness level (TRL) designs.

Despite the flight heritage of the techniques, there is no compact, bulk analysis, dual-mode instrument readily available for upcoming SMaP-constrained missions. These are routine analytical techniques used in typical geochemistry laboratories on Earth, and having an in-house instrument(s) available for JPL missions would be highly beneficial and have many opportunities for infusion into flight. The team is targeting the development of an instrument that will have clear paths to infusion into flight.

The operation of the complete combination instrument concept shown in the CAD model in (a) has been demonstrated in the lab (b) with miniaturized components that have a clear path to flight







SNSPDs

DEMONSTRATING VERY-LONG RANGE OPTICAL COMMUNICATION AND MUCH MORE

A sub-Kelvin cryostat accommodating a 64-element SNSPD array fabricated at MDL deployed in the DSOC Ground Laser Receiver at the 200-inch Hale telescope at the Palomar Observatory.

Superconducting nanowire single photon detectors (SNSPDs) are a critical technology for deep-space optical communication (DSOC) and have been fielded in the ground system for NASA's DSOC technology demonstration mission, launching aboard the Psyche spacecraft. In 2021, with JPL's Optical Communication group, MDL fielded a custom 64-element SNSPD at the Palomar Observatory's 200-inch Hale telescope. Designed, fabricated, and tested at MDL, this unique instrument has a large-area array to efficiently couple to the 5-m telescope through free-space optical windows. It counts single photons with sub-100 picosecond (ps) timing resolution at rates approaching 1 billion counts per second (cps). This will enable the DSOC project to demonstrate free-space optical communication for the first time from interplanetary distances, up to 1000 times the current record. MDL has also contributed detector instruments for the NASA Optical-to-Orion project and for the Deep Space Network (DSN) Aperture Enhancement Project (DAEP) in the RF/optical hybrid communication element. SNSPDs offer the best performance for time-resolved single photon detection at wavelengths from ultraviolet (UV) to mid-infrared (IR). SNSPDs have near-100% detection efficiency at IR wavelengths, exquisite single-photon timing precision down to the few-ps level, and remarkable dynamic range. SNSPD pixels have been demonstrated with dark count rates below 10^{-5} cps and a maximum count rate of 10^{7} cps. MDL, the world-leader in SNSPD development, is setting new performance records.

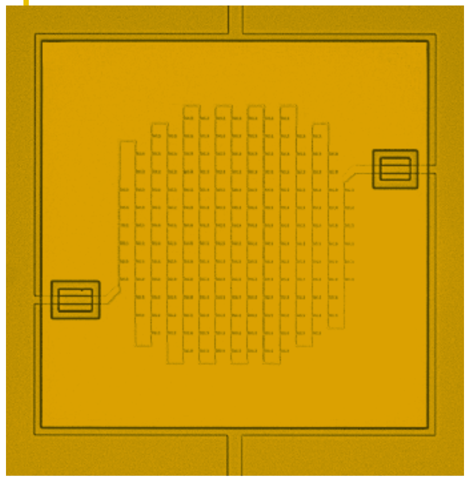
SNSPDs' performance makes them highly relevant for many other applications. MDL is currently developing technology to enhance the speed and fidelity of flight and ground detectors for a future quantum communication technology demonstration concept and is working with Lawrence Berkeley National Laboratory on dark matter detection. Other work aims to interface custom large-area SNSPDs with cryogenic GaAs scintillation targets. Additionally, new mid-IR SNSPDs could probe atmospheres for exoplanet transit spectroscopy. These efforts are part of a longstanding collaboration between JPL, NIST, and MIT and now include PhD thesis research with students from Caltech and the University of Maryland.

MKIDs FOR FAR-INFRARED ASTRONOMY

Investigating star formation over cosmic time requires far-infrared (IR) observations of star-forming galaxies with red shifts from z = 0 to z = 4. Microwave kinetic inductance detectors (MKIDs) use high-Q superconducting microwave resonators to sense faint signals at long IR wavelengths where optical signals break Cooper pairs and modulate the kinetic inductance of the resonator. The superconducting gap energy is 2-3 orders of magnitude smaller than the bandgap of conventional semiconductors, giving MKIDs fundamental advantages in sensitivity compared to conventional technologies. This versatile approach was invented at JPL and Caltech. While never flown on a space mission, MKIDs are currently being baselined for a joint JPL/Goddard mission concept for a probe-class far-infrared observatory (25 – 350µm), as strongly recommended by the Astrophysics 2020 Decadal Survey.

In this observatory, thousands of resonators are coupled to a single microwave feedline, allowing an elegant scaling of the readout with minimal low-temperature components. The readout can then be implemented at room temperature, taking advantage of large-scale industrial developments in software-defined radio (SDR). MKID multiplexing will enable tens of thousands of pixels to allow background-limited wide-field spectral surveys for the first time in the far-IR.

Recent advances in MKID technology include the development of small-volume aluminum MKIDs with a sensitivity approaching 1 x 10^{-19} W/Hz$^{1/2}$, enabling background-limited sensitivity throughout the far-IR. This development relies on MDL's significant material advances and fabrication process developments, including amorphous silicon dielectric materials with ultra-low microwave loss and sensitive fabrication processes for aluminum MKIDs. Significant progress has been made in both simulation and fabrication of devices with optimized optical coupling at short wavelengths (25µm), where high-efficiency MKIDs are challenging to demonstrate. The image shows a small-volume aluminum MKID pixel with an antenna structure optimized for a 25-µm optical band. This work was performed at MDL with input from JPL and in close collaboration with the Caltech groups of Jonas Zmuidzinas and Sunil Golwala.



Optical microscope image of an aluminum MKID optimized for high optical efficiency at 25 µm.

COMPACT INTEGRATED RAMAN SPECTROMETER

A COMMON APPROACH FOR SENSITIVE ANALYSES TO EXPLORE THE MOON AND EUROPA

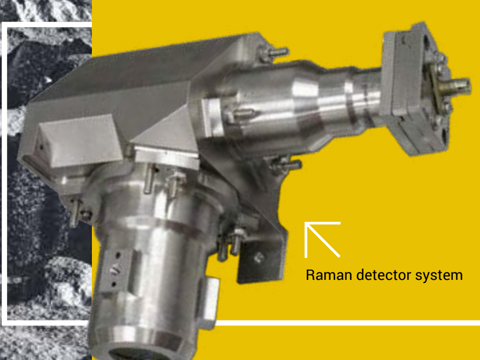
The Compact Integrated Raman Spectrometer (CIRS) is being developed to enable future scientific discovery under two funded NASA programs: Instrument Concepts for Europa Exploration 2 (ICEE-2) and Development and Advancement of Lunar Instrumentation (DALI). Under ICEE-2, MDL will raise the technology readiness level (TRL) of the mechanical, optical, and detector/detector electronics subsystems necessary to allow the instrument to survive the high levels of ionizing radiation present on Europa and tolerate the launch loads and thermal conditions expected. Additionally, an integrated sampling handling system allows the CIRS to examine icy samples (1 cc each) in their frozen, melted and desiccated states. CIRS uses a green laser and a high-resolution spectrometer to collect the Raman spectra of each sample with the resolution necessary to perform definitive mineralogy, quantitatively measure concentrations, and detect organic and potentially biogenic molecules at extremely low concentrations.

In a mission to Europa, an icy sample would be conveyed to CIRS from the moon's surface. After receiving it, CIRS would initially collect spectra from the frozen sample to determine its provenance by measuring the Raman spectra of any entrained salts, such as $MgSO_4$. CIRS is capable of differentiating salts that are in a glassy state, which may originate from one of Europa's plumes, from those in the crystalline form, indicative of much older surface ice. Younger plume ice could be a valuable find since it should have less long-term exposure to ionizing radiation and be more likely to contain less degraded biogenic material than older surface ice.

After CIRS examines the icy sample, it will be melted to randomize the Raman cross-section of its soluble constituents to allow CIRS to quantitatively measure their concentrations. Finally, the sample will be freeze-dried to remove all of the water and thereby concentrate solid constituents on the cup's bottom window.

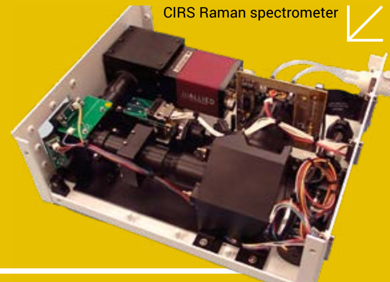
To increase the sensitivity of the measurement even further, the cup's window is specially treated to provide surface enhanced Raman (SERS) capabilities. SERS can often boost the Raman spectra of trace compounds by many orders of magnitude. While conventional SERS substrates have lifetimes that are typically limited to just a few weeks, the CIRS cup window is coated with a thin film of silver chloride, which can remain in an inactive state indefinitely. However, this substrate can be photo-activated by the CIRS laser *in situ* to form a highly SERS-active layer of silver nanoparticles years after launch. This unique approach provides CIRS with the sensitivity needed to make measurements with detection limits for some important organic molecules at parts per billion concentrations.

CIRS is also being developed to explore the Moon under the NASA DALI program. For lunar missions, CIRS can perform detailed investigations of lunar mineralogy to study the effects of space weathering and locate regions containing water ice and hydrated minerals so that they may be used within *in situ* resource utilization (ISRU) processing systems. Under the DALI project, MDL will leverage many of the opto-mechanical subsystems already being developed under ICEE-2 and focus efforts on developing the control electronics and firmware needed to drive the instrument's subsystems and communicate with the spacecraft. The CIRS controller uses the Kintex XQRKU060 FPGA, a chip that can be programmed for a specific use. It is rad-hard to a total ionizing dose (TID) of 100 krad and is designed to exploit triple modular redundancy (TMR) in its firmware architecture to minimize the effects of cosmic-ray-induced single event upset and latch-up events. CIRS will also leverage an existing Kintex-based flight qualified control board called the Common Instrument Electronics (CIE) board that JPL is developing for general use as a flight instrument controller.



Raman detector system

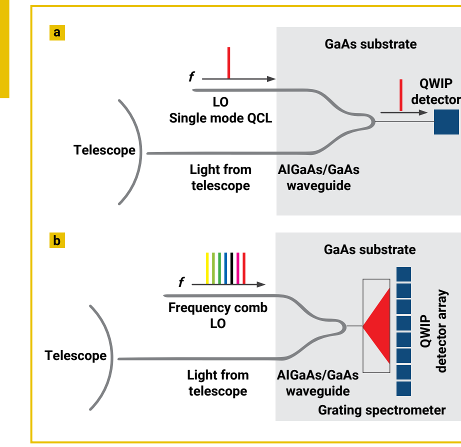
CIRS Raman spectrometer



DETECTORS FOR ASTRONOMY APPLICATIONS

MDL PIONEERS THE DEVELOPMENT OF WAVEGUIDE-COUPLED HIGH-SPEED QUANTUM WELL DETECTORS

Photonic waveguide coupled to a QWIP detector when using (a) a single-element photodetector and a single-mode local oscillator and (b) a linear array of photodetectors in conjunction with a multi-frequency comb.



Long baseline synthesis imaging at very high angular resolution (≤ 0.5 nano-radian or ≤ 100 µas, micro-arcseconds) can revolutionize the astronomical imaging of distant stars, as well as remote sensing for space situational awareness. Targets at room temperature (~300 K), such as exoplanets in habitable-zone orbits, naturally emit in the mid-infrared (IR), making the 8-13 µm window of Earth's atmosphere attractive for the remote sensing of such objects. In the mid-IR, the needed resolution can be achieved with 1-50-km baseline interferometers, and at these separations, traditional direct-detection interferometry becomes difficult or impossible. However, coherent detection with laser heterodyne mixing, together with conversion to fast digital signals, can overcome many of these limitations.

MDL is developing fast heterodyne mixers based on quantum-well infrared photodetectors (QWIPs) embedded in GaAs photonic waveguides and is a leader and pioneer in this technology. This development allows for the detection of long-wavelength light around 10 µm with close to unity quantum efficiencies (QEs) and quantum limited noise at unprecedented electrical bandwidths exceeding 30 GHz. Such detectors are game-changing technology enabling long-baseline heterodyne imaging of distant stars with better than nano-radian angular resolution. Furthermore, the scalability of the III/V material system and its mature fabrication provide a suitable platform for future detector arrays required for applications with more than one THz of measurement optical bandwidth.

The MDL team possesses significant expertise in the design and development of QWIPs and GaAs photonic circuits. The waveguide-coupled QWIP detectors are crucial to improve the QE and simplify the parallelization of large arrays of ~100 mixers with in-built dispersive capability.

In our approach, liquid-nitrogen-cooled QWIPs provide high response and high-speed detection of 10 µm radiation. A highly favorable and rarely exploited intrinsic property of inter-subband QWIPs based on group III-V semiconductor materials is the very short lifetime of their excited carriers, typically on the order of a few picoseconds.

This property has two important consequences: the detector frequency response can reach ~100 GHz, and its saturation intensity is very high ($1e^{7}$ W cm^{-2}). These properties are ideal for a heterodyne detection scheme in which a laser local oscillator (LO) can drive a strong photocurrent (higher than the dark current of the detector) that can coherently mix with a signal shifted in frequency with respect to the LO.

Notably, very high speeds are difficult to obtain in infrared inter-band detectors based on mercury-cadmium-telluride (MCT) alloys, which have a much longer carrier lifetime and therefore a lower-speed response. The mature GaAs/AlGaAs III-V technology enables excellent repeatability, operability and uniformity for both single-pixel and large-area arrays.

However, one drawback of QWIPs that has limited their application is their relatively low QE when illuminated from the top. To efficiently induce inter-subband absorption, it is imperative that the in-coupled electric field of IR radiation be parallel to the growth direction of the quantum wells. For this application, where a linear array of photodetectors is required, QWIP detectors coupled to planar passive optical waveguides will detect light with high QE. The passive optical waveguides support distinct transverse electric (TE) or transverse magnetic (TM) modes whose dominant electric fields are orthogonal to the QWIP quantum well layers and therefore can induce large optical absorption, allowing for the detection of light with close to unity QE.

This basic architecture can then be scaled to support an array of photodetectors coupled to a series of optical waveguides. Because of the unprecedented uniformity of the QWIPs and the accuracy and the robustness of the coupling, this architecture results in a uniform response from the detector array that eases the calibration and operation of the overall system.

A competitive award from the JPL Topical Research & Technology Development (R&TD) fund has enabled MDL to design, grow and fabricate a 10 µm single-pixel QWIP with a high-quality absorption peak. Low loss passive waveguides have now been designed and fabricated.

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Conference Publications

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4. Bae, B., Belousov, A. et al., MEMS Preconcentrator and Gas Chromatograph Chips for the Spacecraft Atmosphere Monitor, 2021 21st International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers), 2021, 58-61. doi: 10.1109/Transducers50396.2021.9495458
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16. Gunapala, S D, Ting, D. et al., T2SL focal planes for compact remote sensing instruments, Proc. SPIE 11723, Image Sensing Technologies: Materials, Devices, Systems, and Applications VIII, 1172302, 12 April 2021. doi: 10.1117/12.2595798 (Keynote Presentation).
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Book Contributions

1. Maestrini, A, Siles, J. V., Signal Generation by Diode Frequency Multiplication: Chapter 9, pp. 323-381, in Pavlidi, D (ed.)., Fundamentals of Terahertz Devices and Applications, John Wiley & Sons, Ltd, 2021.
2. Mehdi, I, THz Applications: Devices to Space Systems: Chapter 13, pp. 511-547, in Pavlidi, D (ed.)., Fundamentals of Terahertz Devices and Applications, John Wiley & Sons, Ltd, 2021.
3. Nikzad, S., Hoenk, M.E., Hennessy, J.J. and Bell, L.D., High Performance Silicon and III-Nitride-Based UV and UV/Optical Imaging Detectors: Chapter 1 pp. 3-33, in The WSPC Handbook of Astronomical Instrumentation: Volume 2: UV, Optical & IR Instrumentation.World Scientific Publishing Co Pte Ltd, 2021.

New Technology Reports

1. Chattopadhyay, G., Khanal, S. et al., Waveguide Based Submillimetere-Wave and Terahertz Variable Attenuator, NTR 52013.
2. Chattopadhyay, G., Lin, R. H. et al., Terahertz Waveguide Switches using Piezo Electric Motors, NTR 51999.
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4. Drevinskas T., Electrospray Compartment for Capillary Electrophoresis-Mass Spectrometry, NTR 51899.
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6. Fradet, M., Briggs, R. M., Islam, K. M., Monolithically Integrated Mid-Infrared Laser-Based Gas Spectrometer on-a-Chip, NTR 51955.
7. Fradet, M., Tosi, L. P. et al., Laser Doppler Velocimetry for Downhole Application, NTR 51920.
8. Hill, C.H, Greer, F., Improvements to III-V Detector Performance using Atomic Layer-Based Surface Treatments, NTR 52104.
9. Khanal, S., Rahiminejad, S. et al., Waveguide Based Submillimeter-Wave and Terahertz Variable Attenuator, NTR 52013.
10. Kraus, H., Simcic, J., Ultraviolet LED-Assisted Vacuum System Water Desorption, NTR 52026.
11. Polk, J., Coleen, M., Jung-Kubiak, C., Liu, Y., (2021) "Indium Electrospray Capillary Force Driven Feed System for Microfabricated Emitter Array Chips," NTR 51556.
12. WRais-Zadeh, M., Jung-Kubiak, C., Coskun, B. C., Toda, R., Shevade, A., (2021) "A non-contact pressure-balanced electrostatically-actuated microvalve," NTR 51926.
13. Sherrit, S., Tosi, L. P. et al., A System for Measuring Multiphase Flow in Downhole Conditions and Flow Regimes, NTR 51924.

Patents

1. Wu, Y. H., Sherrit, S. et al., Tunable Diffraction Gratings Using Surface Acoustic Waves, US Patent App. 17/397, 767
2. Tossi, P., Rais-Zadeh, M. et al., A System for Measuring Multiphase Flow in Downhole Conditions and Flow Regimes, Provisional Patent filed Feb. 2021.
3. Fradet, M., Rais-Zadeh, M. et al., Laser Doppler Velocimetry for Downhole Application, Provisional Patent filed Feb. 2021.

Awards and Recognition by External Organizations

1. Richard Kidd appointed as a Member-at-Large in the American Chemical Society Southern California Section (SCALACS) Executive Committee (2021-present)
2. Goutam Chattopadhyay was Selected Chair, IEEE Microwave Theory and Techniques Society (MTT-S) Membership and Geographic Activity (MGA) Committee
3. Imran Mehdi appointed Editor in Chief, IEEE Transactions on THz Science and Technology.
4. April Jewell elected to the Executive Committee of the American Vacuum Society's Thin Film Division (TFD). Dr. Jewell is already a member of the TFD's Program Committee and serves as the group's Promotion Chair.

MDL Equipment Complement

Material Deposition

- Electron-Beam Evaporators (6)
- Thermal Evaporators (5)
- Angstrom Engineering Indium-Metal Evaporator
- AJA Load Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- PlasmaTherm 790 Plasma Enhanced Chemical Vapor Deposition (PECVD) for Dielectrics with Cortex Software Upgrade
- Oxford Plasmalab System 100 Advanced Inductively Coupled Plasma (ICP) 380 High-Density Plasma Enhanced Chemical Vapor Deposition (HD PECVD) System for Low-Temperature Dielectric Growths with X20 PLC upgrade.
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Beneq TFS-200 Atomic Layer Deposition (ALD) System
- Custom integrated Atomic Layer Deposition and Metal Evaporation system
- Tystar (150-mm/6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 3 Tubes for:
  - » Low-Stress Silicon Nitride
  - » Atmospheric Wet/Dry Oxidation
  - » Oxy-Nitride growths
- Carbon Nanotube (CNT) Growth Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  - » Veeco GEN200 (200-mm/8-inch) Si MBE for UV CCD Delta Doping (Silicon) with computer upgrades
  - » Veeco Epi GEN III MBE (III-V Antimonide Materials)
  - » Veeco GENxcel MBE (III-V Antimonide Materials)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (3)

Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (3)

Lithographic Patterning

- Electron-Beam (E-beam) Lithography: JEOL JBX9500FS e-beam lithography system with a 3.6-nm spot size, switchable 100,000 and 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.) – (2nd system coming on line in 2023)
- Canon FPA3000 i4 i-Line Stepper (0.35-μm res.)
- Canon FPA3000 EX3 Stepper with EX4 Optics (0.25-μm res.)
- Canon FPA3000 EX6 DUV Stepper (0.15-μm res.)
- Contact Aligners:
  - » Karl Suss MJB3
  - » Karl Suss MJB3 with backside IR
  - » Suss MA-6 (UV300) with MO Exposure Optics upgrade
  - » Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
  - » Suss Gamma 4-Module Cluster System
  - » Site Services Spin Developer System
  - » SolarSemi MC204 Microcluster Spin Coating System
- Yield Engineering System (YES) Reversal Oven
- Sonotek Exacta Coat E1027 Photoresist Spray Coater
- Ovens, Hotplates, Furnaces, and Manual Spinners (5)

Dry Etching

- Commonwealth IBE-80 Ion Mill
- Branson Plasma Ashers
- Tepla PP300SA Microwave Plasma Asher
- Fluorine-Based Plasma Etching Systems
- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- PlasmaTherm Versaline Deep Silicon Etcher (DSE/DRIE)
- SPTS Omega LPX Rapier DRIE
- Unaxis Shuttleline Load-Locked Fluorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm APEX SLR Fluorine-based ICP RIE with Laser End Point Detector with SW upgrade
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 Etcher
- Oxford PlasmaPro 100 Cobra Load-Locked Cryo Etching / Atomic Layer Etching / Bosch Etching System, primarily for Black Silicon.

Chlorine-based Plasma Etching Systems

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

Wet Etching & Sample Preparation

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (6), including (1) dedicated for batch processing of 6" wafers
- S-cubed Spray Liftoff and Photoresist Removal Tool
- Rinser/Dryers for Wafers including Semitool 870S Dual Spin Rinser Dryer
- Chemical Hoods (7)
- Acid Wet Processing Benches (5)
- Developer Bench
- KOH/TMAH Bench
- Jelight UVO-Cleaners (2)
- Novascan UV8 Ultraviolet Light Ozone Cleaner
- Tousimis 915B Critical Point Dryer
- Solaris 150 Rapid Thermal Processor
- Polishing and Planarization Stations (4)
- Strasbaugh 6EC Chemical Mechanical Polisher
- Precitech Nanonform 250 Ultra Diamond Point Turning System
- SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool with upgrade
- SurfX Atomflo 500 Argon Atmospheric Plasma Surface Activation System for wafer bonding
- New Wave Research EzLaze 3 Laser Cutting System
- Indonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher
- Laurell Technologies Dilute Dynamic Cleaning System (DDS), Model EDC 650, a Dilute HF/Ozonated DI Water Spin Cleaning System with MKS Instruments Liquizon Ozonated Water Generator.
- Osiris Fixxo M200 TT Wafer Mounting Tool

Packaging

- SET FC-300 Flip Chip Bump Bonder
- Karl Suss Wafer Bonder
- Electronic Visions AB1 Wafer Bonder
- EVG 520Is Semi-Automatic Wafer Bonding System
- Finetech Fineplacer 96 "Lambda" Bump Bonder
- Thinning Station and Inspection Systems for CCD Thinning
- Wire Bonding
- DISCO 320 and 321 Wafer Dicers (2)
- Tempress Scriber
- Pick and Place Blue Tape Dispenser System
- Loomis LSD-100 Scriber Breaker

Characterization

- Profilometers (2) (Dektak XT-A and Alphastep 500)
- Frontier Semiconductor FSM 128-NT (200-mm/8-inch) Film Stress and Wafer Bow Mapping System
- LEI 1510 Contactless Sheet Resistance Tool
- Jandel Model RM3000+ 4-Point Probe System
- FISBA μPhase 2 HR Compact Optical Interferometer
- Woollam RC2 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
- Filmetrics F54-EXR
- Bruker Dimension 5000 Atomic Force Microscope (AFM)
- Park Systems Inc. NX20 Atomic Force Microscope (AFM)
- KLA-Tencor Surfscan 6200 Surface Analysis System Wafer Particle Monitor with Upgraded Software (2)
- Hitachi Regulus 8230 UHR Cold Field Emission Scanning Electron Microscope (SEM) with Aztec Energy Dispersive X-ray Microanalysis System and Critical Dimension Measurement Capabilities
- Nanospec 2000 Optical Profilometer
- Nikon and Zeiss Inspection Microscopes with Image Capture (3)
- Keyence VHX-5000 Digital Microscope including low power lens
- McBain BT-IR Z-Scope IR Microscope Workstation
- Olympus LEXT 3D Confocal Microscope
- Mitaka NH-5Ns 3D Profiler
- Electrical Probe Stations (4) with Parameter Analyzers (2)
- RPM2035 Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectrometers (3) including Bruker Optics Vertex 80 FTIR
- PANalytical X'Pert Pro MRD with DHS High Temperature Stage X-ray Diffraction System
- Surface Science SSX501 XPS with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- VEECO / WYKO NT 9300 Surface Profiler (including 50X optics)
- Zygo ZeMapper non-contact 3D Profile
- Thermo Scientific LCQ Fleet CE / MS (Capillary Electrophoresis / Mass Spectrometer) System
- Lakeshore Cryotronics Model CPX 1.7 Kelvin Cryo Probe Station
- Blufors Cryogen-Free Dilution refrigerator

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