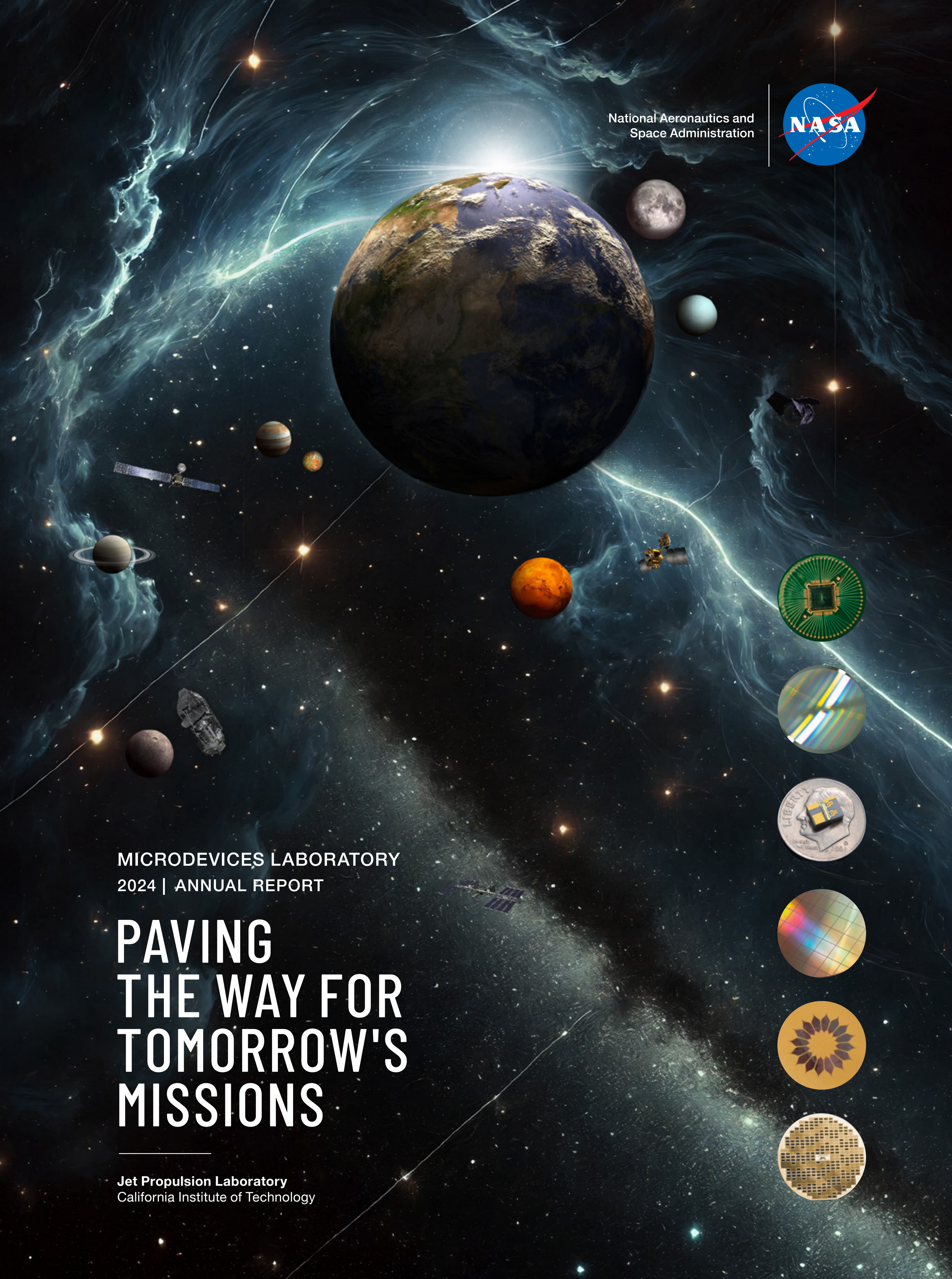


National Aeronautics and Space Administration

MICRODEVICES LABORATORY
2024 | ANNUAL REPORT

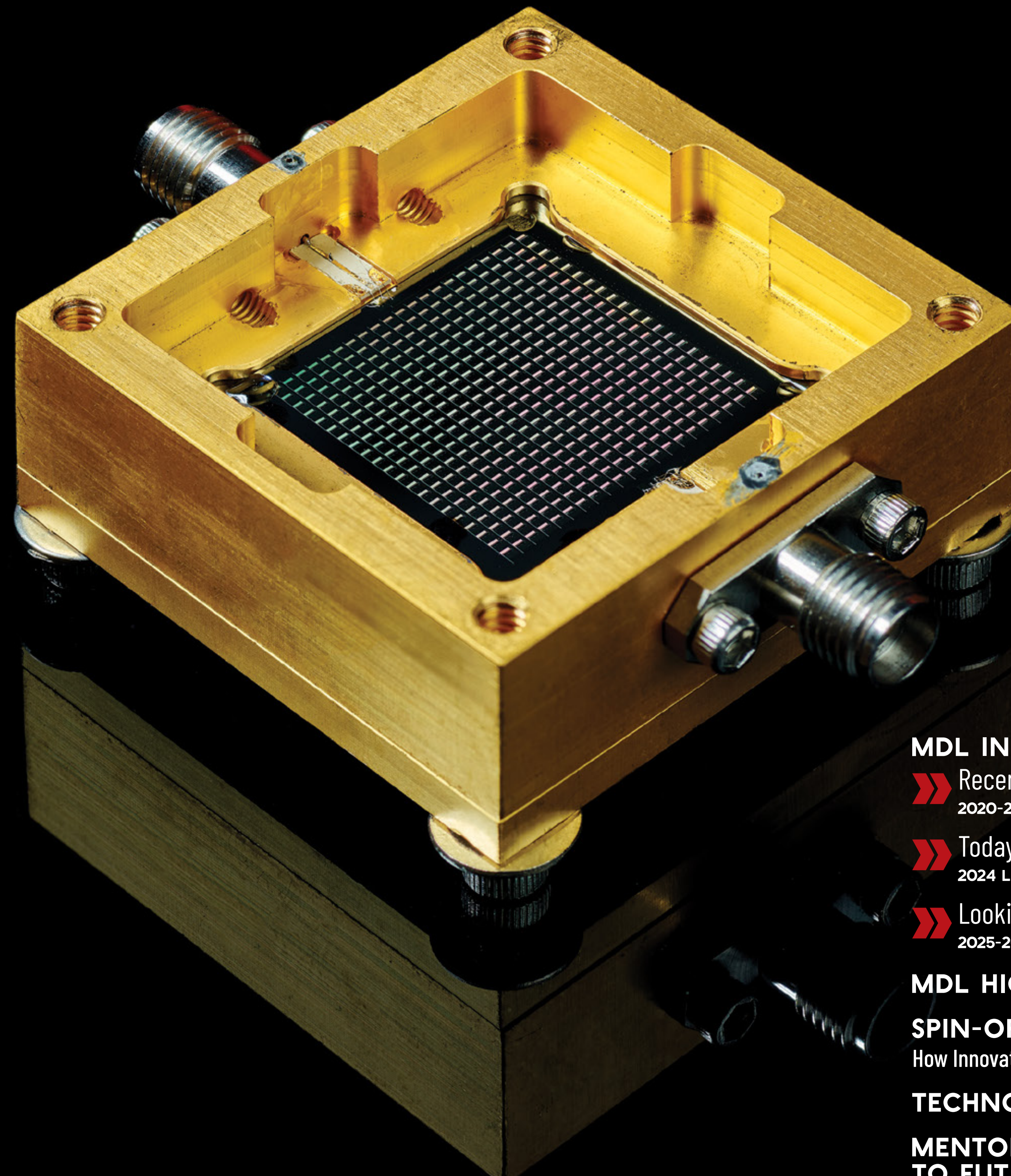
PAVING THE WAY FOR TOMORROW'S MISSIONS

Jet Propulsion Laboratory
California Institute of Technology

MDL — A STORY OF CONTINUOUS ACHIEVEMENT

For the past 30 years, MDL has been infusing new technologies into instruments in support of NASA missions. MDL aligns component deployments and technology developments with NASA's Decadal Surveys and strategic plans. By following their recommendations and guidelines, MDL supports competitive proposal and mission-concept formulation. Sustained backing from JPL leadership ensures MDL has state-of-the-art equipment, the proper infrastructure and, most importantly, a world-class workforce of microdevice engineers.

With this sustained investment, MDL devices will continue to be delivered far into the future, serving the whole science community and helping answer humankind's most pressing questions.



CONTENTS

JPL DIRECTOR'S MESSAGE

Laurie Leshin
Director, Jet Propulsion Laboratory

Our commitment and focus at JPL are to drive the forefront of scientific discovery and benefit humanity through first-of-a-kind research, technology innovation, and groundbreaking space missions. The Microdevices Laboratory (MDL) plays an important role in achieving this objective by inventing, developing, and delivering novel microdevice technologies that enable new capabilities, instruments, and missions. The success of MDL, building on investments of the past decade and before, is exemplified by devices that have flown and contributed to missions of the past two years. These include the Near Infrared Spectrometer and Photometer on ESA's EUCLID Space Telescope, Spacecraft Fire Safety Experiment (SAFFIRIE-VI) Combustion Product Monitor (CPM), PSYCHE — Deep Space Optical Communication, International Space Station Spacecraft Atmospheric Monitor (ISS SAM), Fluidic Operations in Reduced Gravity Experiment (FORGE), Hyperspectral Thermal Imager (HyTI), Polar Radiant Energy in the Far-Infrared Experiment (PREFIRE), Tanager-1 Imaging Spectrometer, and the Mapping Imaging Spectrometer (MISE) on Europa Clipper. These results demonstrate MDL's commitment to fulfill its charter across all elements of NASA. Looking forward, a diverse range of MDL devices are planned for launch in 2025 and beyond. You will find more information about these and other contributions to NASA's mission throughout this annual report.

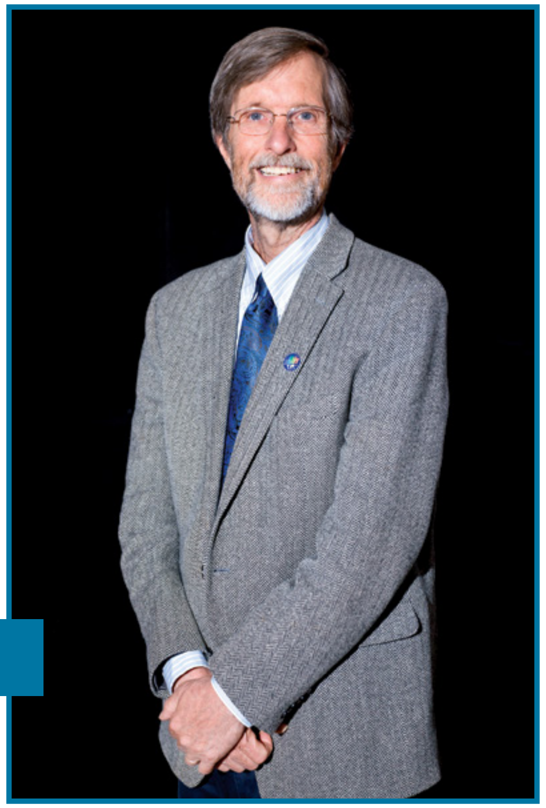
In addition to the specialized applications for space-based science, we are excited when MDL devices find broader application and we can collaborate with commercial partners to transfer these technologies to industry. Examples of successful transfer extend back to the beginning of MDL with the invention of CMOS imagers by Eric Fosum. Subsequent examples include the semiconductor lasers used in the Tunable Laser Spectrometer (TLS) on the Mars Curiosity rover and more recently High Operating Temperature Barrier Infrared Detector (HOTBIRD) infrared detectors. Over the history of MDL, these and other novel space science-inspired devices have been successfully commercialized, enhancing American technology leadership.

Today, the MDL team is engaging with scientists and technologists across NASA and elsewhere to conceive and invent the new devices, technologies, and capabilities that will be needed by NASA as we look to future exploration and discovery, and work to improve life on our home planet.

MDL continues its exceptional track record of inventing, maturing, and delivering new microdevice technologies and capabilities for next-generation missions, instruments, and projects for NASA and our nation. This success is exemplified by the wide range of devices launched and deployed in space over MDL's more than three-decade history. In this annual report, we are excited to share many recent space device successes, along with current device development efforts. Wherever possible, we are especially committed to working with our customers to shorten the time from initial concept to the flight of new devices in space.

MDL has a broad range of development efforts, including new devices for measuring the electromagnetic spectrum from x-rays to millimeter wavelengths with improved precision and accuracy while enabling reduced instrument size, mass, and power requirements. Beyond the electromagnetic spectrum, MDL is supporting novel device development that will enable next-generation mass spectrometers, seismometers, gravity gradiometers, magnetometers, microelectromechanical systems, as well as systems to detect and measure the molecules of life in space. In support of these advancements for NASA, focused investments are being made in people, equipment, and facilities. MDL is currently investing in advanced ASML optical lithography capabilities and equipment to develop and fabricate high-temperature magnesium diboride superconducting devices. These investments will enable advances in kinetic inductive detectors, quantum capacitance detectors, superconducting nanowire single-photon detectors, and much more.

Across these efforts, MDL is focused on developing new devices that can be qualified to operate in space and deliver new capabilities for NASA space missions. These efforts include a wide range of collaborations with other NASA centers, government agencies, and industry, with a commitment to supporting NASA across the Science, Exploration Systems Development, and Space Technology Directorates. In this endeavor, we are especially thankful for the hard work and exceptional dedication of the MDL team. As you read this annual report, please reach out if you have questions or see opportunities for new partnerships and collaborations for the benefit of NASA and our nation as we prepare for the missions of tomorrow.



Robert O. Green
Director, Microdevices Laboratory

MDL SUPPORTING NASA INTO THE FUTURE

S.1

MDL IN FLIGHTS

» **RECENT ACHIEVEMENTS**
2020-2023 LAUNCHES

» **TODAY'S DEPLOYMENTS**
2024 LAUNCHES

» **LOOKING BEYOND TOMORROW**
2025-2040 LAUNCHES

MDL DEVICES AND TECHNOLOGIES CONTINUE TO BE SUCCESSFULLY DELIVERED.

Because new technology developments regularly take 10 or more years to come to fruition, MDL's rich legacy has been sustained through consistent investment over its history.

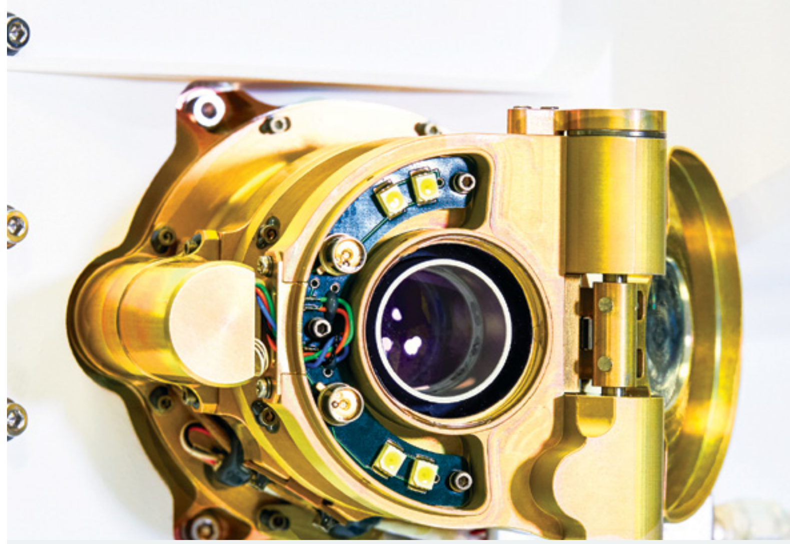
MDL devices and technologies have been successfully delivered for years, with many more in development for deployment in the short- and long-term future. With its many contributions to JPL and NASA, MDL has been pivotal to these agencies' pasts and core to their futures.

2020-2023 LAUNCHES

RECENT ACHIEVEMENTS

Over the past few years, MDL has infused various new technologies into NASA missions, from novel superconducting detectors to delta-doped and UV bandpass-optimized detectors to unique GC-MS and microfluidic components.

MDL's combination of equipment and processes also supported the delivery of gratings for spectrometers and X-ray analysis instruments, with devices now operating on Mars, on the ISS and aboard multiple NASA orbiters.



SHERLOC

LOOKING FOR SIGNS OF PAST LIFE

Top: SHERLOC is aboard Perseverance.

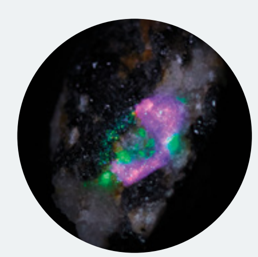
The Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument was launched to Mars on the Perseverance rover to take high-spatial-resolution images of Martian geology that capture both structure and texture.

The spectroscopy it conducts will help identify trace organic materials on the Martian surface. Its data, combined with that from PIXL, will help better understand the history of water on Mars and whether the planet was ever home to life.

Additionally, the combined data will help identify a target landing area for the future Mars Sample Return campaign.

Above: SHERLOC contains a UV grating from MDL that produces excellent spectra with near-theoretical-maximum diffraction efficiency and negligible scatter.

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



MDL FABRICATED SHERLOC'S UV GRATING FOR MARS 2020

PIXL

The Planetary Instrument for X-ray Lithochemistry (PIXL) was sent to Mars on the Perseverance rover to understand the elemental composition of Martian rock using X-ray fluorescence. By gathering elemental signatures, the instrument can lookfor signs of previous life on Mars and help determine the best location for collecting samples to be returned to Earth on a future mission.

Additionally, using structured light illuminators (SLIs) to produce patterns of laser spots on the ground, PIXL can autonomously avoid hazards. Because there are no commercially available gratings that meet the requirements of the SLIs, MDL custom fabricated them using e-beam lithography and etching onto a fused silica substrate. By using a binary design, the gratings could be fabricated in only two steps: e-beam patterning followed by fused silica etching.

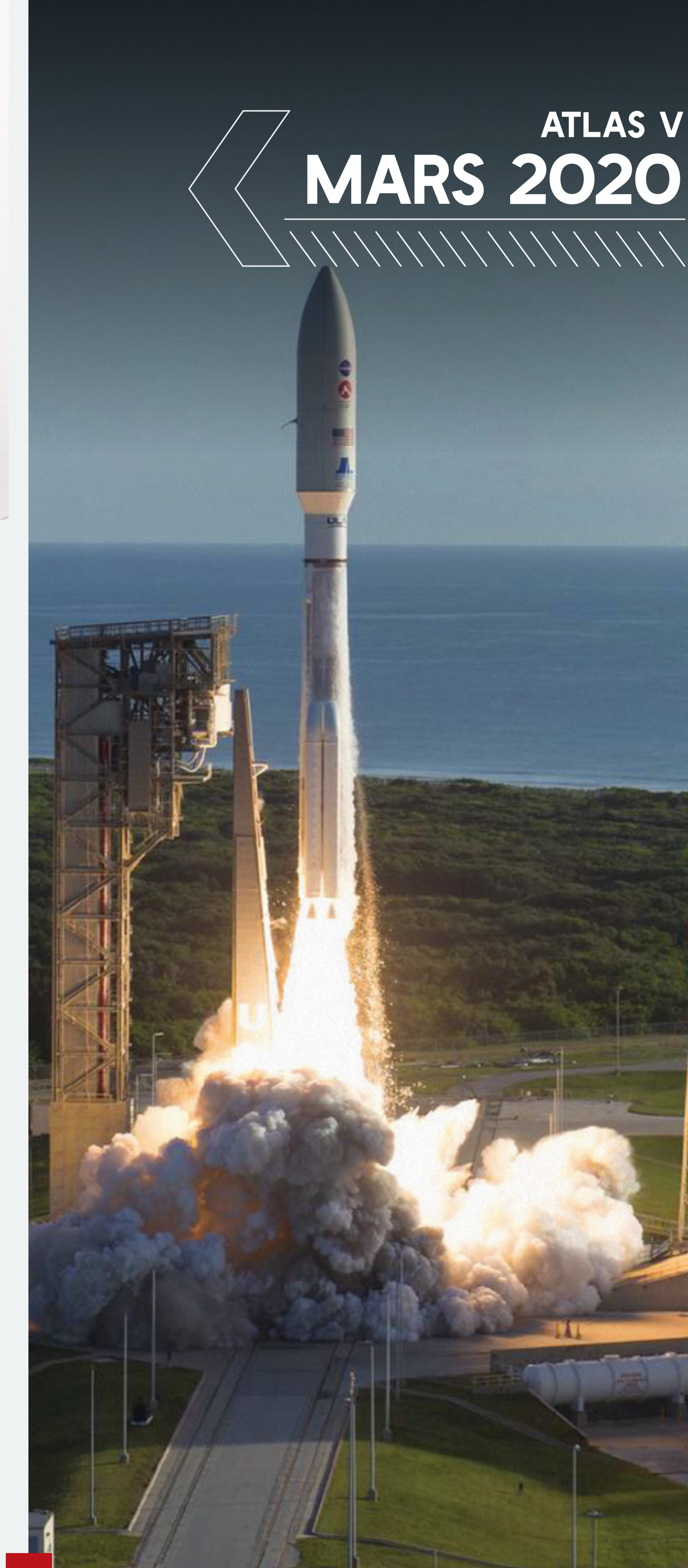
Top: PIXL instrument engineering model in test.

PIXL'S SPOT-ARRAY GENERATOR GRATINGS WERE MADE BY MDL FOR MARS 2020

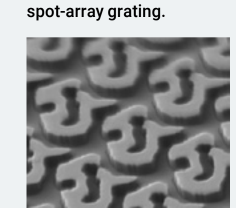
07.30.20

ATLAS V

MARS 2020

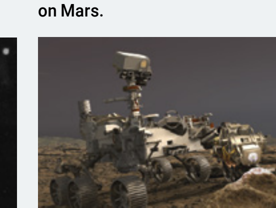


Below: SEM image of the seven-by-seven spot-array grating.



Below: Seven-by-seven spot array produced by 830 nm infrared laser transmitted through the left CGH grating.

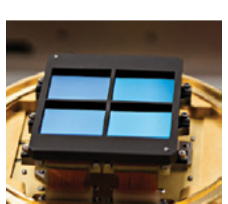
Below: At the rover's arm's end, PIXL and SHERLOC can reach rock targets within centimeters on Mars.



12.25.21

ARIANE 5
JWST

JWST IS RETURNING DATA THAT IS CHANGING OUR VIEW OF THE UNIVERSE



Left: JWST's NIRCam Optical System is a 16-megapixel mosaic of light sensors. The mosaic is comprised of four separate chips mounted together with a black mask covering the gaps between the chips.

NIRCam CORONAGRAPH

A 30-year track of MDL flight component development culminates in an outstanding mission.

The successor to the Hubble Space Telescope, the James Webb Space Telescope (JWST) was launched to expand the spectral range, enhance the image sharpness, and exponentially increase the sensitivity of its predecessor.

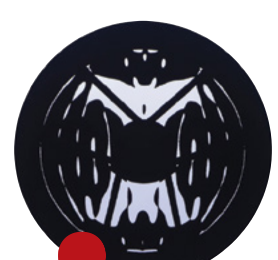
JWST's primary imager is the Near-Infrared Camera (NIRCam), which has not only returned revolutionary data but was also crucial in aligning and verifying the deployment of JWST's 18 mirrors, together making up a single 6.5-meter primary mirror.

NIRCam also contains a coronagraph that is enabled by five flight occulting masks fabricated at MDL. These masks have enabled the detection, imaging, and characterization of exoplanets, and the telescope itself has made contributions to our understanding of the universe that cannot be overstated.

MDL SUPPORTED THE DEVELOPMENT OF JWST'S PRIMARY IMAGER

Top: JWST reveals the Pillars of Creation in vibrant near-infrared colors.

Right: JWST NIRCam Coronagraph with MDL e-beam-fabricated occulting masks.



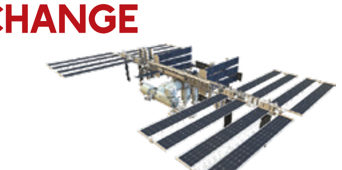
IMAGING SPECTROMETER

The Earth Surface Mineral Dust Source Investigation (EMIT) uses its imaging spectrometer to pinpoint sources of carbon dioxide and methane emissions.

In the past two years, EMIT has captured over 55,000 50-square-mile "scenes" of the planet and identified over 750 point-source emitters of greenhouse gases all over the world. The data are publicly available, creating an opportunity to develop strategies to mitigate these emissions and improve the accountability of emitters.

The mission has been extended for at least two more years and supports over a dozen additional studies that will use EMIT data to investigate myriad processes on Earth, from snow's role in the water cycle to methane emissions in arid regions. See page 40 for more information.

THE DATA EMIT GENERATES WILL HELP DRIVE SOLUTIONS TO MITIGATE CLIMATE CHANGE



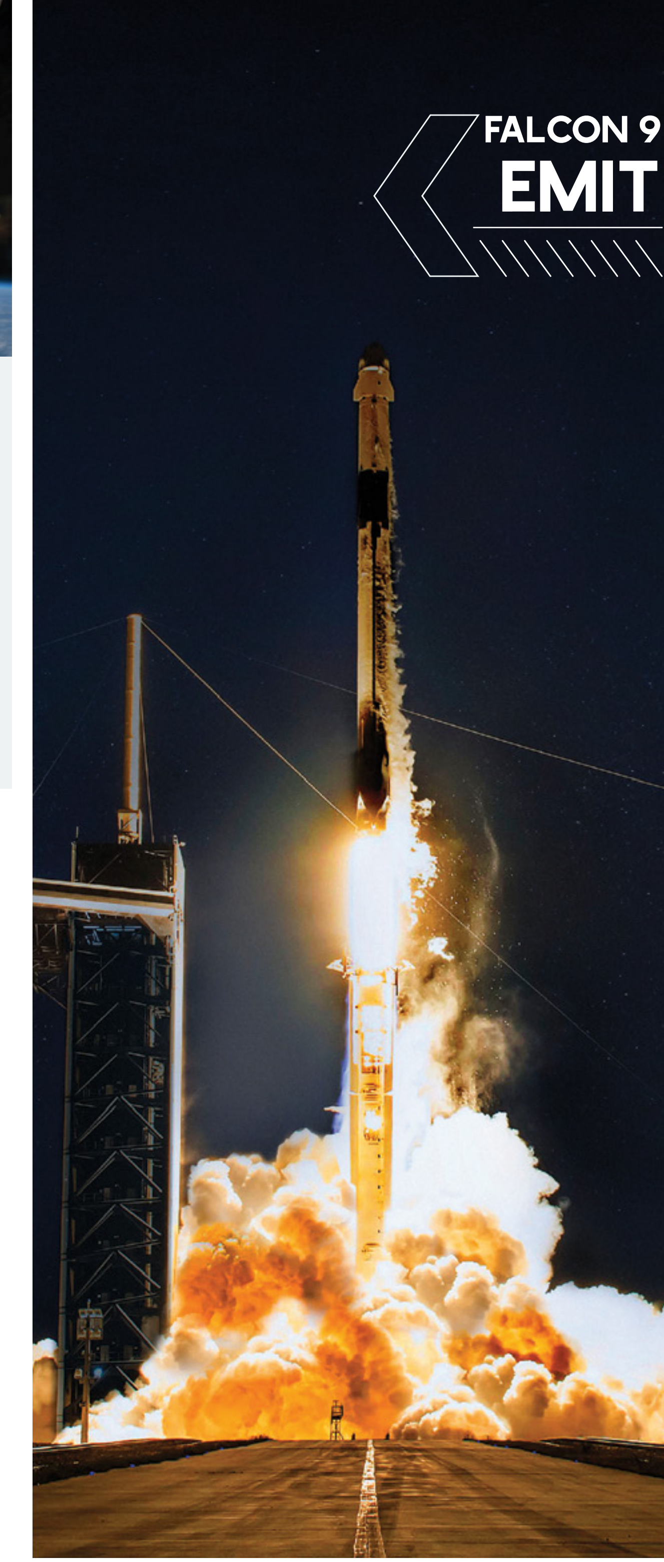
Top: The EMIT instrument observes Earth from outside the International Space Station.

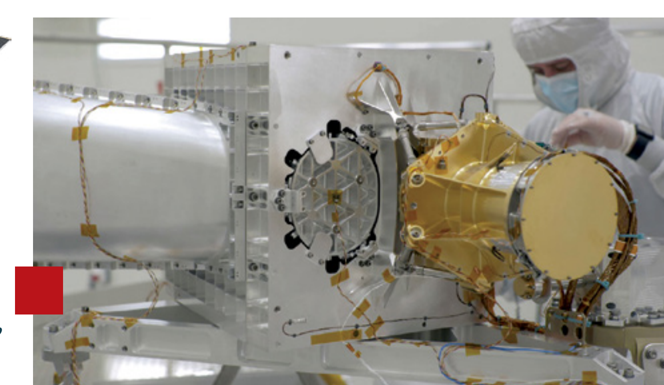
Right: MDL-e-beam-fabricated structured blaze concave grating technology for the EMIT imaging spectrometer.

The EMIT imaging spectrometer requires a specialized concave reflection grating, optical slit, and zero-order light trap fabricated using MDL's unique combination of equipment and processes.

07.14.22

FALCON 9
EMIT

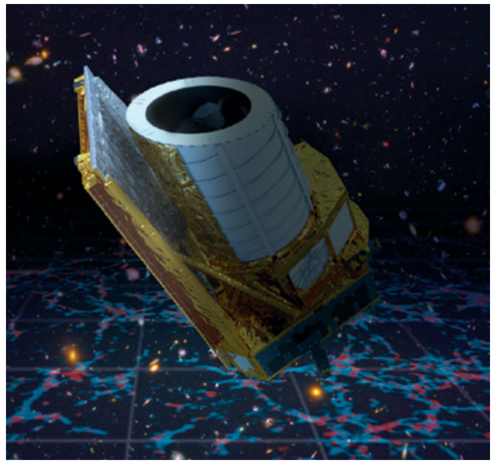




07.01.23

FALCON 9

EUCLID



An artist's concept of the Euclid spacecraft.

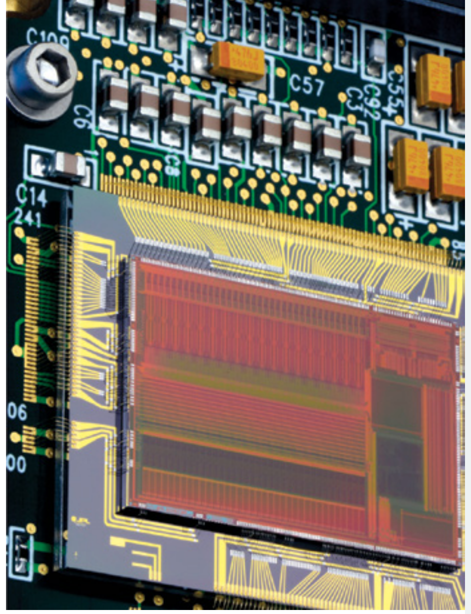
FLIGHT PACKAGING

With limited initial data, the Euclid space telescope is already making discoveries about the distant universe, identifying rogue planets, and using gravitational lensing to understand dark matter and dark energy.

The European Space Agency's Euclid space telescope launched with a goal of improving our understanding of dark matter and dark energy by creating a 3D map of the universe that spans 10 billion light-years.

Two instruments enable this mapping: the VISible instrument and the Near-Infrared Spectrometer and Photometer (NISP). Euclid's first public images were released in early 2024 and show, among other phenomena, gravitational lensing in a galaxy cluster.

UNRAVELING THE MYSTERIES OF DARK MATTER AND DARK ENERGY



Cryogenic electronics packaging for Euclid.

MDL'S CONTRIBUTIONS TO EUCLID HAVE BEEN HIGHLY VALUABLE

The cryogenic (cold) portion of the Euclid space telescope's NISP instrument. Credit: Euclid Consortium/CPPM/LAM.

After an external delivery failure from thermal cycling stress in the application-specific integrated circuit packaging for the NISP instrument, MDL led the recovery effort and manufactured key components. MDL and JPL also led the procurement and delivery of the NISP's detectors.

The Combustion Product Monitor instrument with the cover removed from the optical sensing region.

COMBUSTION PRODUCT MONITOR

Fire aboard a crewed spacecraft is supremely dangerous for astronauts, but precisely because of that danger, there is limited knowledge of fire's behavior in space.

A series of six Spacecraft Fire Safety Demonstration (Saffire) experiments over the course of eight years sought to study different types of fires in microgravity to help improve spacecraft design and better prepare astronauts to respond if a fire were to break out on a crewed spacecraft.

Saffire-VI, the final mission in the series, tested material flammability and gas dynamics in microgravity and with different oxygen levels over nine unique tests. The Saffire experiment operated inside the Cygnus NG-19 S.S. Laurel Clark uncrewed resupply spacecraft from December 22 to 24, 2023, after departing from the International Space Station.

During the Saffire-VI tests, the MDL-fabricated Combustion Product Monitor instrument, a five-channel laser absorption spectrometer, measured the concentrations of O_2, CO, CO_2, HCl, and HF present in the spacecraft cabin, helping better understand the properties of fires and combustion-related gases under these conditions. The mission concluded in January 2024 with the spacecraft burning up as it reentered Earth's atmosphere.

MDL DESIGNED, FABRICATED, TESTED, AND DELIVERED THE COMBUSTION PRODUCT MONITOR INSTRUMENT

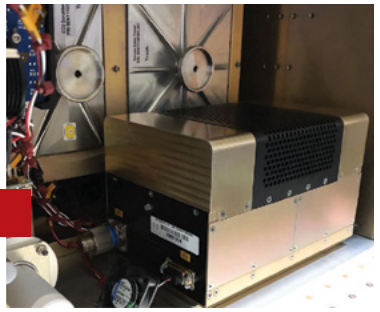
08.04.23

CYGNUS NG-19

SAFFIRE-VI

LASER-BASED INSTRUMENT FOR THE QUANTITATIVE MONITORING OF COMBUSTION-RELATED GASES

The Cygnus NG-19 resupply spacecraft arriving at the International Space Station on August 4, 2023, with the Saffire-VI experiment aboard.



The Combustion Product Monitor instrument installed in the Saffire-VI Far Field Diagnostics unit.

09.25.23

BALLOON
FIREBALL-2

DELTA-DOPED AND UV-OPTIMIZED EMCCD DETECTORS

The Faint Intergalactic medium Redshifted Emission Balloon-2 (FIREBall-2) is a suborbital balloon mission designed to discover and map faint emissions from the circumgalactic medium of low-redshift galaxies ($0.3 < z < 1.0$).

These observations can improve our understanding of galactic and stellar evolution by providing critical insight into the temperature, density, and metallicity of cosmic gases. The rest wavelength emission/absorption lines of many of important tracer species are in the ultraviolet (UV), and for nearby galaxies — including the Milky Way — they cannot be observed from the ground. Thus, FIREBall-2 observes from 120,000 feet in the stratosphere, where a narrow UV window (195-215 nm) allows for these important measurements. The FIREBall-2 mission uses a delta-doped electron-multiplying charge-coupled device (EMCCD) as the science detector; the detector's response is optimized for the stratospheric UV window using a custom antireflection coating developed at JPL.

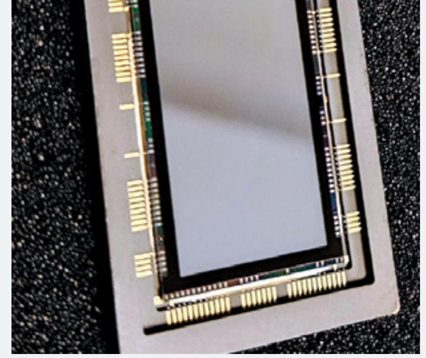
This detector demonstrates high quantum efficiency and very low noise, improving instrument performance by more than an order of magnitude over FIREBall-1, which used a spare microchannel plate from the Galaxy Evolution Explorer (GALEX) as the science detector.

Funded by NASA's Astrophysics Research and Analysis (APRA) program, FIREBall-2 has been an important platform for technology advancement. The first FIREBall-2 flight (2018) successfully demonstrated the full functionality of the detector subsystem in a suborbital environment.

The team acquired 90 minutes of science data during the 2018 flight, demonstrating improved sensitivity over FIREBall-1. A second launch occurred in September 2023; however, a hole in the balloon caused it to descend prematurely. The mission team safely terminated the flight and recovered the payload.

For its next flight, the FIREBall-2 detector system will be upgraded with a new detector board and delta-doped UV EMCCD detector. The new detector will include a UV bandpass filter with high throughput in the FIREBall-2 bandpass with an order of magnitude out-of-band rejection. These custom UV bandpass filters will suppress red leakage, allowing for higher signal-to-noise observations of faint UV signals in a high visible background. The device-integrated UV bandpass filter is a state-of-the-art technology developed at MDL and is baselined for the Star-Planet Activity Research CubeSat (SPARCS), as well as multiple mission concepts currently under development.

This work is part of the long-term collaboration between MDL and Caltech, along with several domestic and foreign institutions.



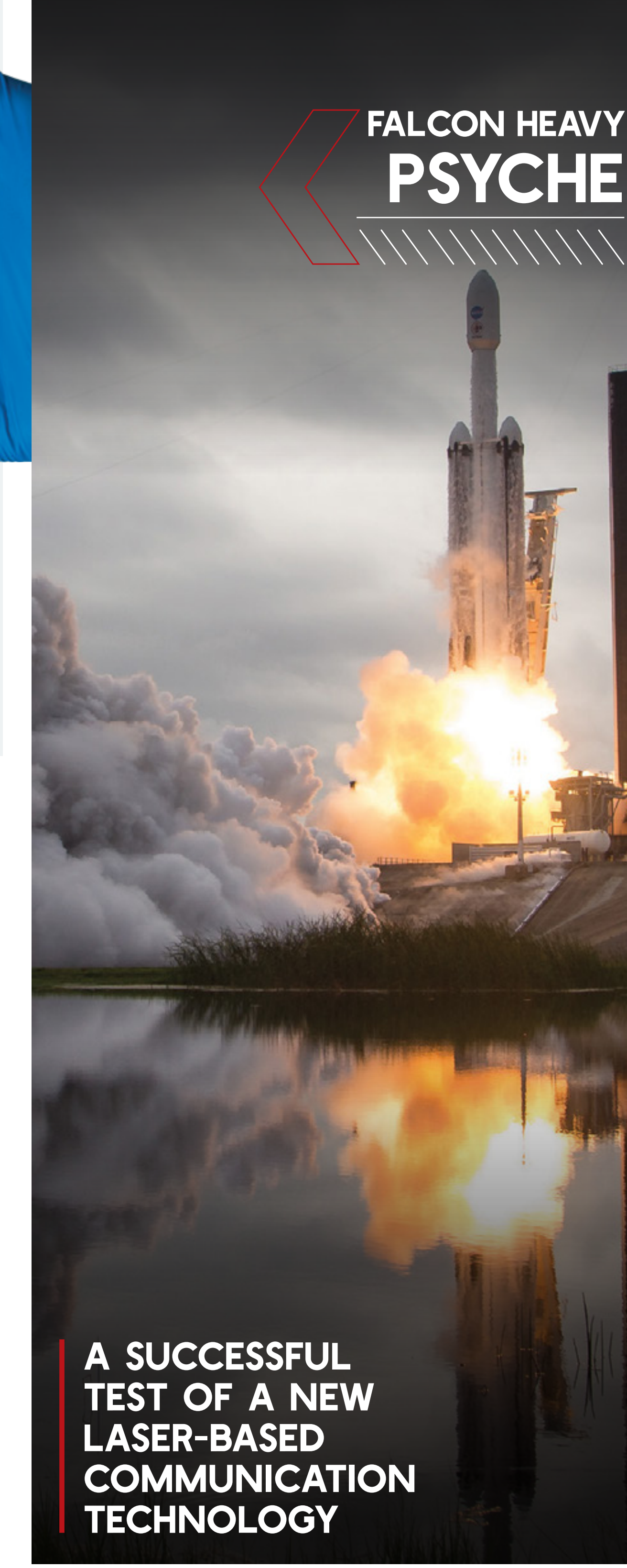
Above: The FIREBall flight device features a UV bandpass filter that reflects most visible light, providing significant rejection.

Above: Preparing the FIREBall gondola for transport to launch site.

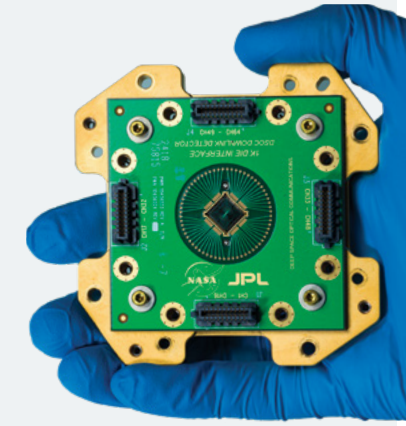
THE FIREBALL-2 BALLOON HAS COMPLETED TWO FLIGHTS AND IS SCHEDULED FOR A THIRD

MDL contributed FIREBall-2's delta-doped and UV bandpass optimized EMCCD detectors. FIREBall-2's next flight is planned for Fall 2025.

10.13.23



FALCON HEAVY
PSYCHE



GROUND RECEIVER FOR DSOC

The mission will investigate a unique metal-rich asteroid and test a new laser communication technology.

Although radio frequencies remain the standard means for transmitting data from space, the Deep Space Optical Communications (DSOC) demonstration will use laser beams to enhance data transmission from deep space.

The goal of DSOC is to demonstrate data transmission rates that are tenfold higher than those currently observed with radio communications. So far, it has exceeded expectations.

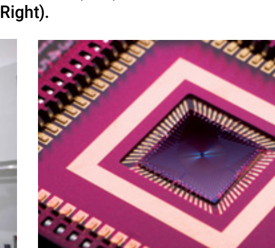
Riding aboard the Psyche spacecraft, the demonstration successfully sent a set of engineering data from 140 million miles away, or 1.5 times the distance between Earth and the Sun. The project team has also been able to send data to the DSOC transceiver and conduct a successful "turnaround experiment" in which data was sent from Earth to the transceiver and then returned to Earth the same night.

Even at 140 million miles away, the demonstration was able to return data at the rate of 25 Mbps, which far surpassed the goal of 1 Mbps. By all accounts, DSOC is successfully ushering in a new standard for deep space communication.

A SUCCESSFUL TEST OF A NEW LASER-BASED COMMUNICATION TECHNOLOGY

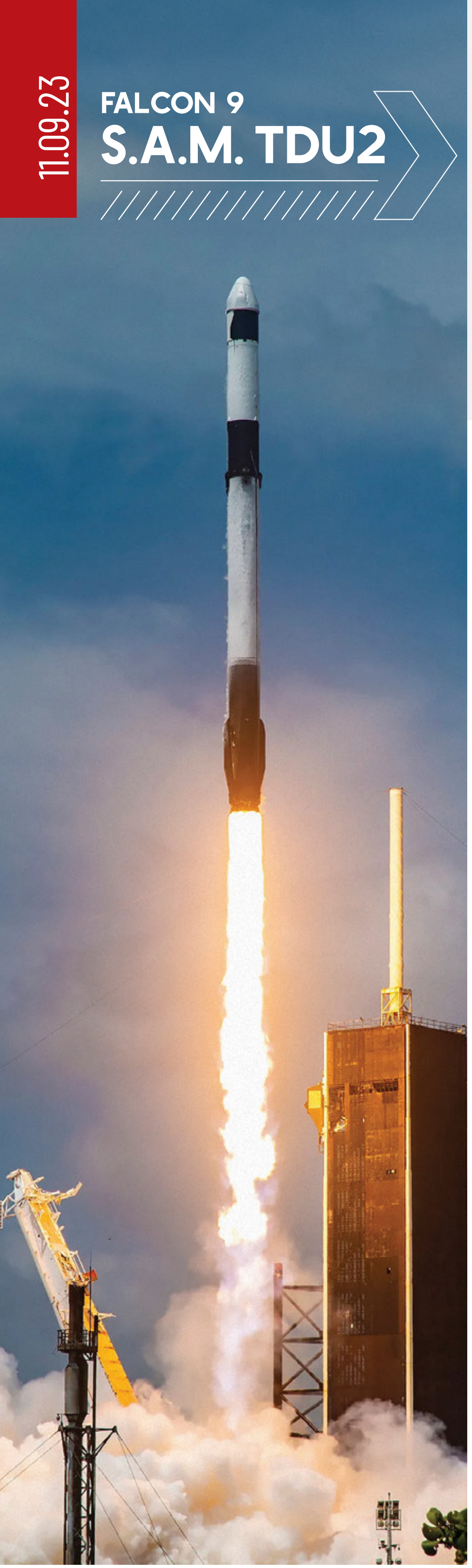
COMMUNICATION IS POSSIBLE FROM 140 MILLION MILES AWAY

Below: The Psyche spacecraft is shown in a clean room at the Astrotech Space Operations facility near Kennedy Space Center in Florida (Left). 64-element SNSPD focal plane array developed by MDL for DSOC (Right).



11.09.23

FALCON 9
S.A.M. TDU2



MEMS COMPONENTS

Good air quality within a crewed spacecraft is of the utmost importance to secure astronaut health.

To monitor air quality on spacecraft using a technology dmonstration, the Spacecraft Atmosphere Monitor (S.A.M.), a miniaturized gas chromatograph mass spectrometer (GC/MS), began development in 2015, and its first technology demonstration unit (TDU1) was deployed on the International Space Station (ISS) in 2019. TDU1 built upon its predecessor, the Vehicle Cabin Atmosphere Monitor (VCAM) instrument, and included three improvements: a passive pumping system, operation under high vacuum conditions, and microelectromechanical system (MEMS) components.

While TDU1 was on the ISS, a second technology demonstration unit (TDU2) was developed with enhanced capabilities. TDU2 incorporated trace gas analysis (TGA) facilitated by a MEMS integration block (MIB) that includes three key innovations: a preconcentrator (PC), a microvalve (MV), and a gas chromatograph (GC). The MV orchestrates the precise regulation of gas flow within the MIB during different steps of the TGA mode. It also overcomes older MVs' tendency to get stuck in the open or closed position. In tandem with the MEMS MV, the PC and GC have undergone various design updates and rigorous testing as part of the subassembly. The PC, although less than 1.4 µL in volume, can help detect chemicals in the parts per billion range. The MIB is integrated with a JPL-developed quadrupole-ion trap MS (QITMS), which enables high vacuum operation during TGA. The MV chip, with five electrostatic microvalves, plays a pivotal role in controlling carrier and sample flow. MDL fabricated the PC, GC and high pressure MVs for the GC/MS.

The TDU2 aluminum chassis is 9.5" x 8.75" x 7.5" in volume with a mass of 9.5 kg.

TDU1 returned to JPL in January 2022 and is being refurbished with MDL MIB to add TGA capabilities. It will rejoin TDU2 on the ISS in late 2024, enabling both units to operate simultaneously.

12.19.23

BLUE ORIGIN NS-24
FORGE

The Fluidic Operations in Reduced Gravity Experiment (FORGE) is a microfluidic instrument payload designed to observe the behavior of mixed phases (gas/liquid) in a microfluidic system.

FORGE-2 IS PLANNED FOR LATE 2024

FORGE simulates pneumatically driven reservoirs that are an important component of microfluidic analytical chemistry instruments, such as ion chromatographs or the Organic Capillary Electrophoresis Analysis System (OCEANS).

Versions of OCEANS are being developed for use in microgravity to monitor water quality for astronauts and search for evidence of life on potential future ocean world missions. Due to their small volumes and dimensions, microfluidic systems are dominated by capillary forces, which make them adaptable to microgravity environments.

However, there are some exceptions, such as the need for moderately larger volume reservoirs that hold stocks of reagents or enable mixing, diluting, and other fluidic manipulations. In these cases, it can be advantageous to have two-phase (gas/liquid) reservoirs, but maintaining well-separated phases in microgravity can be challenging.

FORGE was developed to investigate these two-phase phenomena and demonstrate a fluidic system capable of reliably separating gases from liquids during microgravity operations. FORGE was designed to utilize conical fluidic storage chambers that, due to surface effects, preferentially orient the fluid toward one side of the cone (where the fluidic entrance/exit port is positioned).

Additionally, due to the weak magnetism of water, a permanent magnet was used to evaluate the effect of magnetically induced buoyancy on gas bubbles. All the mission success criteria were met for FORGE operations, and good initial data points on these passive phase separation approaches were acquired.

FORGE was successfully launched on December 19, 2023, as one of 33 experimental payloads aboard Blue Origin's New Shephard rocket flight NS-24. A second flight scheduled for late 2024 will test FORGE in gravity environments similar to the Moon and Europa.

MDL developed the custom electronics, software, and 3D printed microfluidic systems and manifold needed to analyze extremely small sample volumes.

Microfluidic Mixed Fluids Testbed from MDL.

2024
LAUNCHES

TODAY'S DEPLOYMENTS

This year, MDL is delivering unique and finely optimized components for a long-wave IR focal plane array; a thermopile detector array; and numerous gratings, slits and stray light traps for instruments that will operate from as close as Earth orbit to as far away as Jupiter.

03.21.24

FALCON 9
CRS-30
HyTI

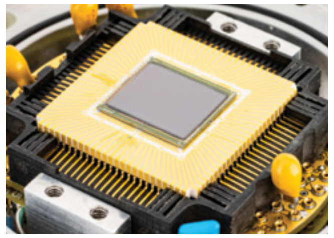
LWIR HOT-BIRD FPA

The Hyperspectral Thermal Imager (HyTI) was a 6U CubeSat technology demonstration whose objective was to monitor both water use and volcanic gases from space using temporal resolution thermal infrared (TIR) imagery acquisition.

HyTI was to cover 30 spectral channels from 8.0-10.7 µm from its orbit 430 km above Earth. The main questions the mission sought to answer revolved around water use in agriculture — where water is being used, how much, and how efficiently — to better understand how to promote food and water security in a warming world with a rapidly growing population. Secondarily, HyTI was to measure the gases emitted from magma, enabling the prediction of volcanic eruptions.

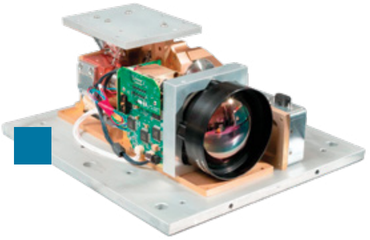
MDL supplied HyTI's long-wave infrared (LWIR) high operating temperature-barrier infrared detector (HOT-BIRD) focal plane array (FPA) and its Dewar cooler assembly. Unfortunately, the HyTI SmallSat was a victim of the G5 geomagnetic storm that occurred May 10-11, 2024.

However, its successor, HyTI-2, is being assembled with the goal of launching in October 2025. See page 36 for more information.



Above: 24-µm pixel pitch, 640 × 512 pixel LWIR HOT-BIRD FPA.

Below: HyTI instrument based on HOT-BIRD FPA.



MDL's contributions to HyTI include its LWIR HOT-BIRD FPA and its Dewar cooler assembly.

THERMOPILE DETECTOR

The Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE) mission uses two CubeSats to understand the emission patterns of far-infrared (FIR) radiation from Earth's poles and how clouds and water vapor affect those patterns.

The two PREFIRE satellites have different polar orbits, enabling them to make frequent measurements of the poles that will allow the characterization of polar FIR emission patterns on the scale of hours to months.

The CubeSats' combination of spectral range (5-45 µm) and spatial resolution make the mission the first of its kind. By characterizing FIR radiation at the poles at wavelengths greater than 20 µm, the mission will further clarify how Earth's surface and atmosphere interact with each other to affect climate change, thus filling an important knowledge gap in current climate change models. See page 38 for more information.

THE HIGHEST DENSITY THERMOPILE ARRAY (64 × 8) FABRICATED AT MDL TO DATE IS PART OF THE PREFIRE FOCAL PLANE ASSEMBLY

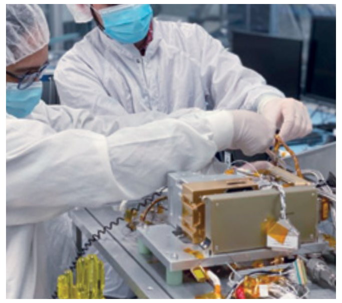
PREFIRE's instrument was designed by JPL and includes a thermopile detector array designed and fabricated by MDL embedded within a fully customized focal plane module.

05.25.24

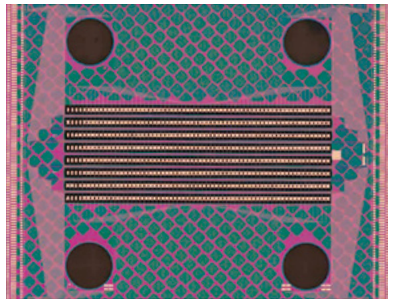
ELECTRON
PREFIRE-1

06.05.24

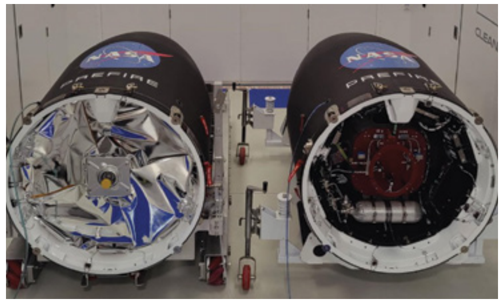
ELECTRON
PREFIRE-2



Thermal InfraRed Spectrometer for PREFIRE.



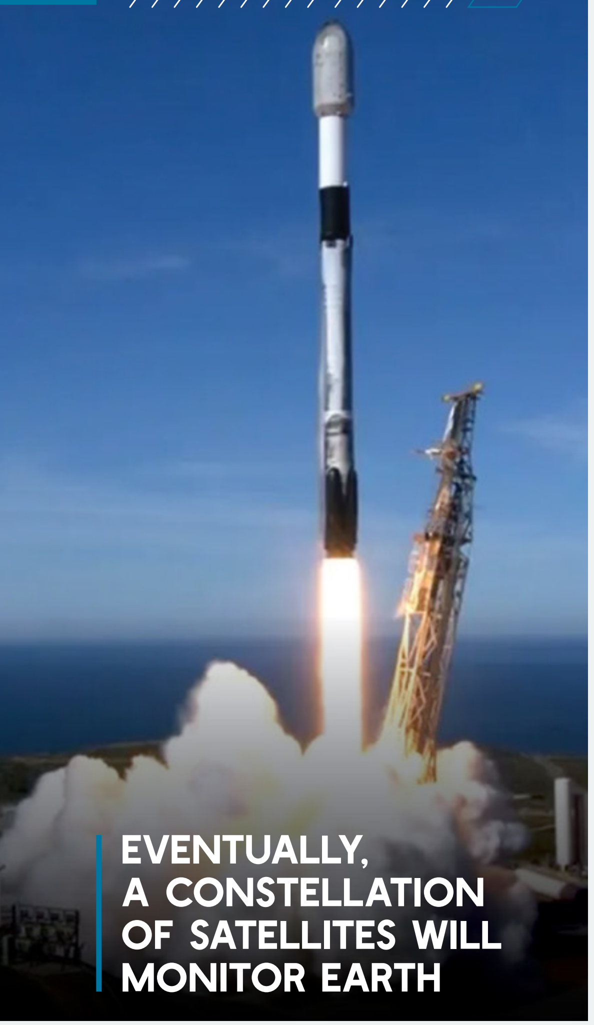
Flight 64 × 8 thermopile array with diamond-pattern micromachined design reduces noise by 30-50% via lowered capacitance.



The Electron fairings for NASA's two PREFIRE launches. Credit: Rocket Lab.

08.16.24

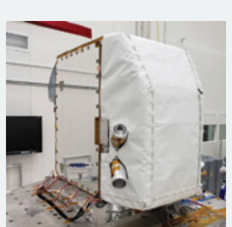
FALCON 9
TANAGER-1



EVENTUALLY, A CONSTELLATION OF SATELLITES WILL MONITOR EARTH

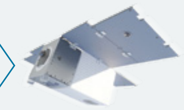
Carbon Mapper Imaging Spectrometer.

Artist's concept of Carbon Mapper Coalition's Tanager satellite.



Imaging Spectrometer fully integrated.

CARBON PLUME MAPPER



In a unique public-private partnership, Carbon Plume Mapper (CPM) designed to identify point source emitters of greenhouse gases worldwide, helping mitigate the risks of global warming.

Identifying greenhouse gas (GHG) emissions such as methane and carbon dioxide on a global scale takes constant vigilance. Efforts to achieve this goal are being spearheaded by the nonprofit Carbon Mapper, Inc., which has developed a public-private consortium aimed at developing and launch GHG point source mapping satellites.

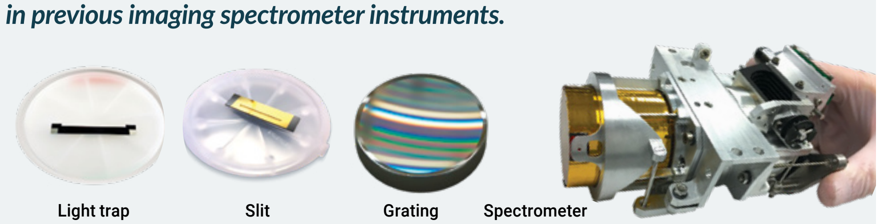
The first of these, Tanager-1, is designed to detect methane emissions at rates as low as approximately 100 kg/h and also measure carbon dioxide with a mean revisit time of 3.5 days. Tanager-1 will be followed by others, and the data they gather will be used to offer methane leak detection services to facility operators and regulators, certify methane levels for oil and gas supply chains, improve transparency about global GHG emissions, and facilitate data-driven solutions to reduce these emissions.

Partners involved in the initiative include funders Bloomberg Philanthropies and the High Tide Foundation; RMI, which is guiding use case applications for the methane data; the University of Arizona and Arizona State University, which are providing scientific expertise; the California Air Resources Board, which maintains policy leadership; and Planet, which is designing and building the satellites.

JPL is providing the imaging spectrometer design and MDL components that enable the state-of-the-art imaging spectrometer for pointing the locations where GHGs are being released.

Tanager-1 launched into orbit from Vandenberg Space Force Base in California on August 16, 2024. The first data sets have exceeded expectations. Plans for launching Tanager-2, -3, and -4 are in development.

> *The gratings, slits, and stray light traps are the result of more than a decade of MDL electron-beam diffractive optics fabrication development and refinement, as well as use and testing in previous imaging spectrometer instruments.*



Light trap Slit Grating Spectrometer

MISE

The Mapping Imaging Spectrometer for Europa (MISE), part of the Europa Clipper mission, will characterize the surface chemistry of the icy moon and compare it to the chemical signatures of Earth's oceans to determine whether Europa may be capable of supporting life.

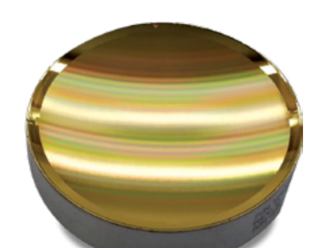
Of all the known places in the solar system that may harbor life, Jupiter's moon Europa is among the most promising. Europa has an icy crust covering deep oceans that may contain more water than all the oceans on Earth, and these vast oceans may house chemical compounds that are required for life to evolve.

Consequently, the Europa Clipper mission's main science goal will be to determine whether there are regions on this icy moon that are capable of supporting life. One related science objective is to characterize the composition of the ice layer. To help achieve these objectives, Europa Clipper will conduct 50 flybys of the moon, using MISE to look for salts and organic compounds in the icy shell. MISE will also characterize variations in surface temperature, which may indicate plume activity and will help better understand how the ice crust and the ocean interact. MISE will operate at global (≤10 km), regional (≤300 m) and local (~25 m) scales using push broom observations. It works at F/1.4 and covers a spectral range from 0.8 to 5 µm (near-infrared to mid-infrared), enabling the detection of salts and organics that might be conducive to life.

It has 10 nm spectral resolution, an instantaneous field of view of 250 µrad/pixel, and a swath width of 300 active pixels. The data generated by MISE will likely be the best information obtained about the composition of Europa's oceans for many years.

The Europa Clipper, NASA's largest planetary mission spacecraft, was fully assembled at JPL in January 2024. In March, it underwent rigorous testing to ensure instrument performance under space-like conditions. It launched on October 14, 2024, with planned flybys of Mars in 2025 and Earth in 2026. The spacecraft carries nine instruments, including MISE.

> *While not a life detection mission, MISE data will help understand whether Europa could support life.*



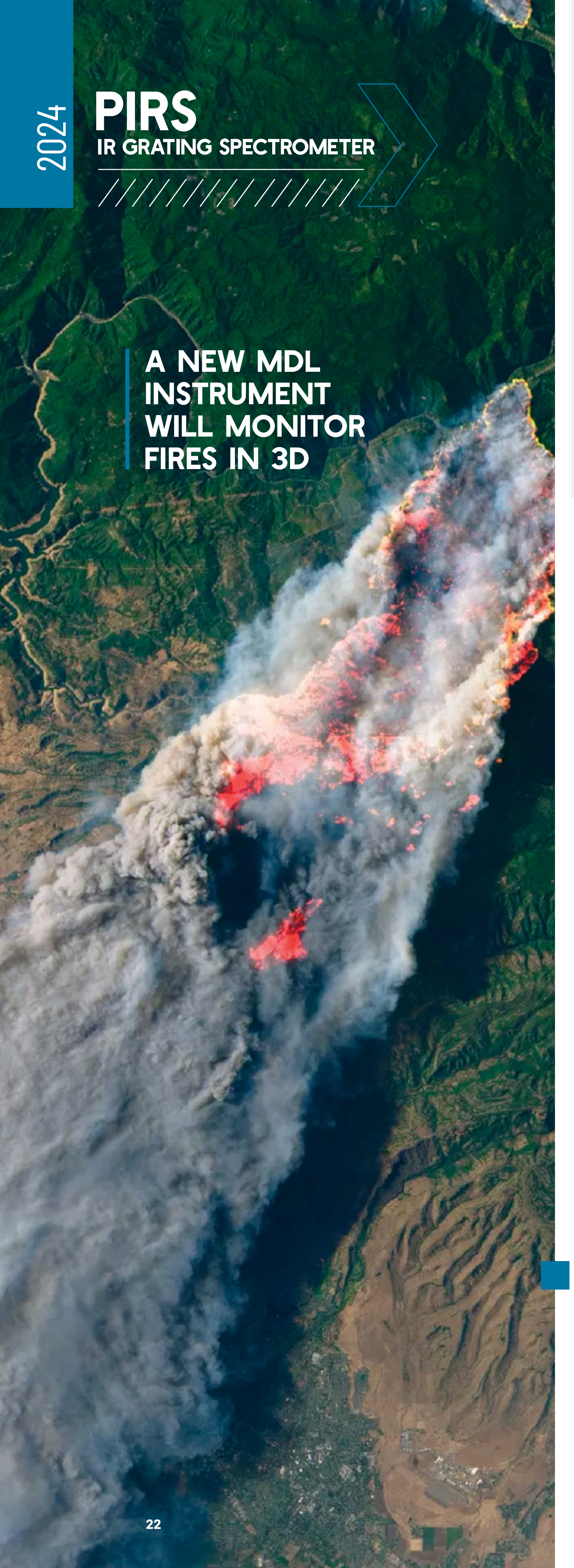
Above: Concave grating for MISE.

10.14.24

FALCON HEAVY
EUROPA CLIPPER

Above: Europa Clipper prepares for test in space simulator.

MDL FABRICATED MISE'S DIFFRACTION GRATING, SLIT, AND ZERO-ORDER LIGHT TRAP



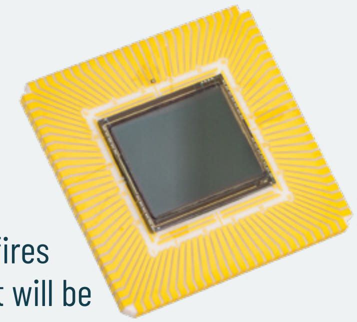
2024

PIRS

IR GRATING SPECTROMETER

A NEW MDL INSTRUMENT WILL MONITOR FIRES IN 3D

IR DETECTORS

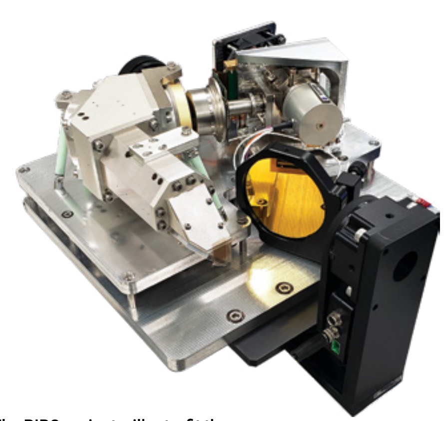


As Earth warms and wildfires become more common, it will be important to understand how these fires start and spread. With that goal in mind, the Pyro-atmosphere Infrared Sounder (PIRS) will soon be deployed and begin monitoring the planet's wildfires.

PIRS will use a grating on a prism, or "grism," and a high operating temperature-barrier infrared detector (HOT-BIRD) to achieve a threefold size reduction compared with older sounders.

Its spatial resolution of ~15-470 m and wide swath of 20 km at 8.5 km altitude will yield high-resolution 3D data on the atmosphere above and around fires as they occur, increasing the available data on wildfire behavior and supporting better firefighting strategies.

For these reasons, NASA's Earth Science Technology Office (ESTO) selected PIRS as one of its first two projects for funding.



Above: The PIRS project will retrofit the CIRAS brassboard. The brassboard includes flight-design optics and HOT-BIRD FPA.

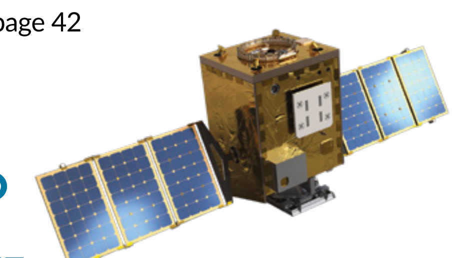
PIRS IS ENABLED BY MDL'S GRATING, BLACK SILICON, AND HOT-BIRD TECHNOLOGY

MAPPING LUNAR WATER

For many years, humans have suspected that water exists on the Moon, but the first confirmation of water outside of permanently shadowed areas occurred only recently. Since then, a key goal has been to determine the overall distribution and form of water on the Moon.

The Lunar Trailblazer mission will achieve this goal by using two instruments aboard a SmallSat that will orbit the Moon. The first instrument, the Lunar Thermal Mapper (LTM), is being developed by the University of Oxford to measure temperature. The other instrument, the High-resolution Volatiles and Minerals Moon Mapper (HVM³), is an imaging spectrometer being developed by JPL that will determine the form of water on the lunar surface. HVM³ will also determine whether the location or state of lunar water changes with exposure to sunlight. In this way, the mission will generate data about the lunar water cycle, a phenomenon whose study is still very new.

Lunar Trailblazer was selected for funding in 2019 as part of NASA's Small Innovative Missions for Planetary Exploration (SIMPLEx) program. It will be a ride-along mission on another launch scheduled for late 2024. See page 42 formore information.

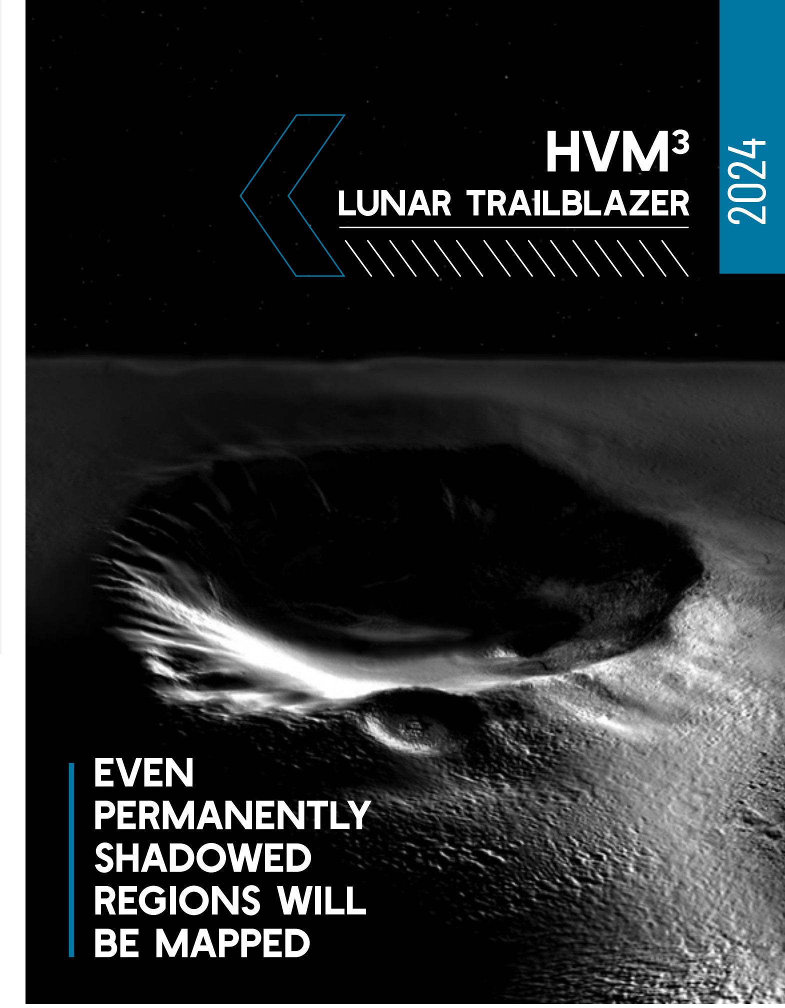


MDL SUPPORTED THE MISSION BY FABRICATING THE GRATINGS, SLIT, AND ZERO-ORDER LIGHT TRAP FOR HVM³

HVM³

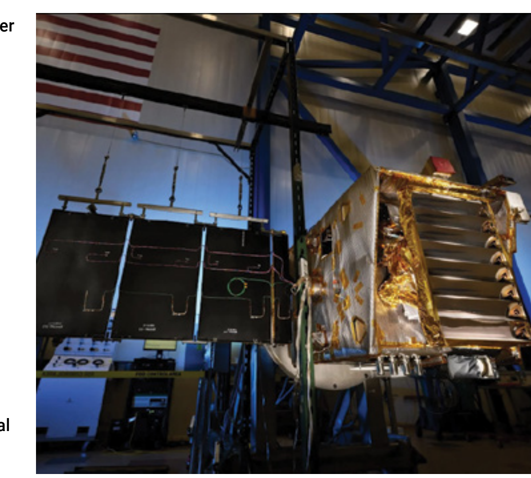
LUNAR TRAILBLAZER

2024

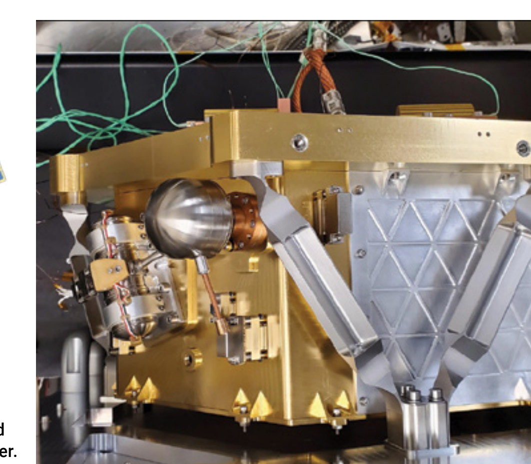


EVEN PERMANENTLY SHADOWED REGIONS WILL BE MAPPED

Above: Illustration depicts water ice in the Moon's permanently shadowed regions.



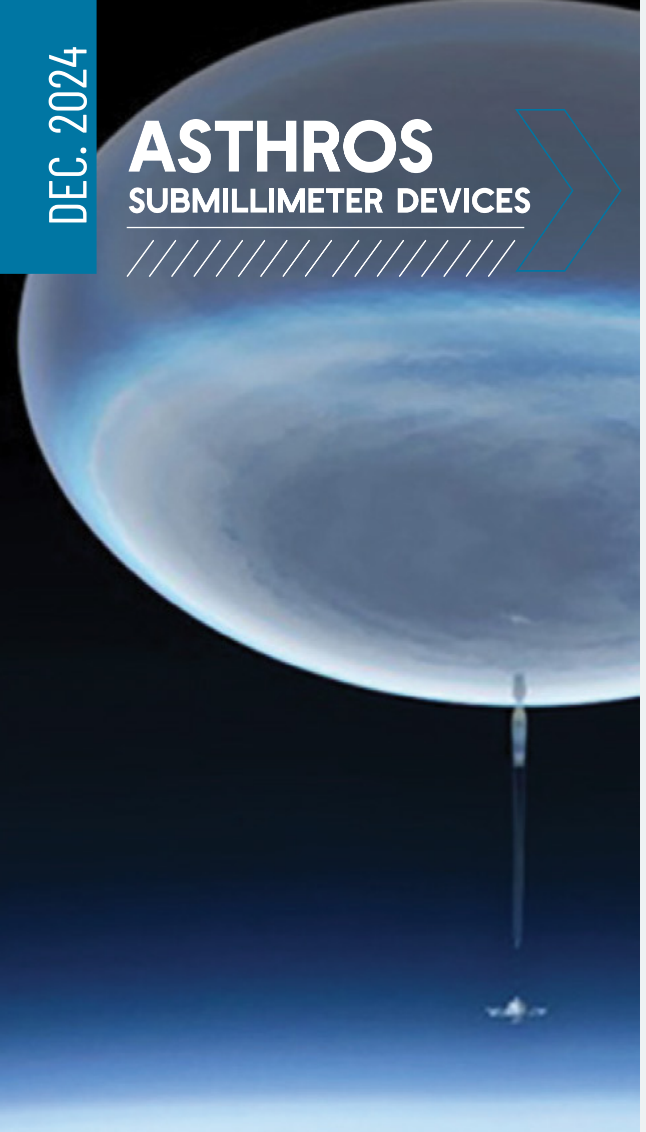
Right: Lunar Trailblazer spacecraft in a clean room after undergoing environmental testing. Credit: Lockheed Martin Space.



Right: HVM³ is one of two instruments that will be carried aboard NASA's Lunar Trailblazer. Credit: Lockheed Martin.

ASTHROS

SUBMILLIMETER DEVICES



HIGH-ALTITUDE BALLOON MISSION

ASTHROS, carried by a stadium-sized balloon, will use an advanced telescope to observe light wavelengths invisible from the ground. The weeks-long mission relies on one of the largest telescopes ever flown on a high-altitude balloon.

The Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths (ASTHROS) observatory will launch from Antarctica and monitor light wavelengths from high above Earth's atmosphere.

ASTHROS benefits from cutting-edge MDL technology featuring a 2.5 m antenna that detects far-infrared emissions never seen before in high spectral resolution.

During the instrument's 3-4 week flight, ASTHROS will focus on a selection of star-forming regions in our galaxy and nearby galaxies.

To investigate stellar feedback, ASTHROS will use a technique called high-spectral-resolution spectrometry, which allows scientists to identify specific chemical elements in gas and dust clouds and precisely measure the density and dynamics of those elements.

ASTHROS will be the first mission to conduct high-spectral-resolution spectrometry in a few specific wavelengths of light and identify two specific nitrogen ions that are formed by the processes that drive stellar feedback. This strategy will enable astronomers to create 3D maps of star-forming regions to learn about the influence of stellar feedback. See page 45 for more information.

When a star forms, it affects the formation of nearby stars in a process known as stellar feedback. Little is known about how stellar feedback works, but the processes that drive it are known to generate nitrogen ions with faint spectra at ~1.46 and ~2.46 THz – wavelengths that are blocked by Earth's atmosphere.

Left: An image of the ASTHROS mission's 8.2-foot primary mirror.

MDL CONTRIBUTED THE ASTHROS INSTRUMENT'S SCHOTTKY DIODE-BASED FREQUENCY MULTIPLIED LOCAL OSCILLATORS AND ITS SUPERCONDUCTING HOT ELECTRON MIXERS

SPRITE

UV MIRROR COATINGS

EXPLORING GALACTIC EVOLUTION WITH A CUBESAT MISSION

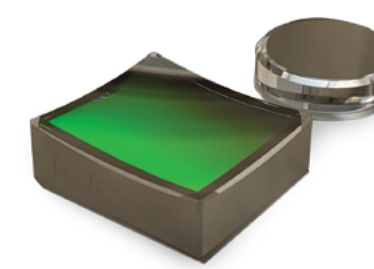
The Supernova Remnants and Proxies for Re-Ionization Testbed Experiment (SPRITE) CubeSat mission will study many of the processes involved in galactic evolution.

Funded by NASA and led by the University of Colorado, the SPRITE CubeSat mission will explore how gas and dust are processed in galaxies due to star formation and supernovae, as well as how ionizing radiation from hot stars travels into the intergalactic medium.

The instrument will operate in the ultraviolet (100-175 nm) and demonstrate cutting-edge coating technologies based on atomic layer deposition (ALD).

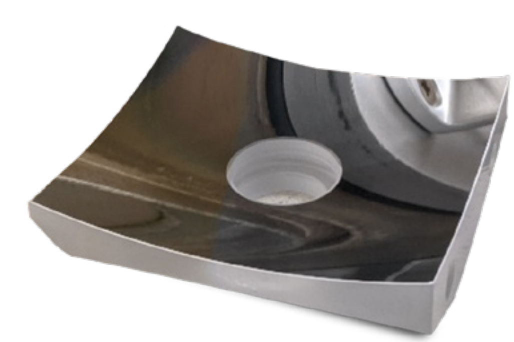
Because ALD coating is uniform, dense enough to protect the material below from moisture and degradation, and thin enough to minimize additional optical absorption loss, mirrors with this coating show superior performance.

In addition to supporting the development of these new coating processes, MDL has also applied these coatings to SPRITE's primary mirror, fold mirror, and grating. The data obtained about SPRITE's performance will inform advances that will be used on future missions such as Aspera, which will also study galactic evolution, as well as flagship missions like the Habitable Worlds Observatory. See page 44 for more information.



Above: Primary grating and witness.

SPRITE WILL REVEAL HOW GALAXIES EVOLVE, AND ITS FIRST OBSERVATION WILL BE OF THE MILKY WAY

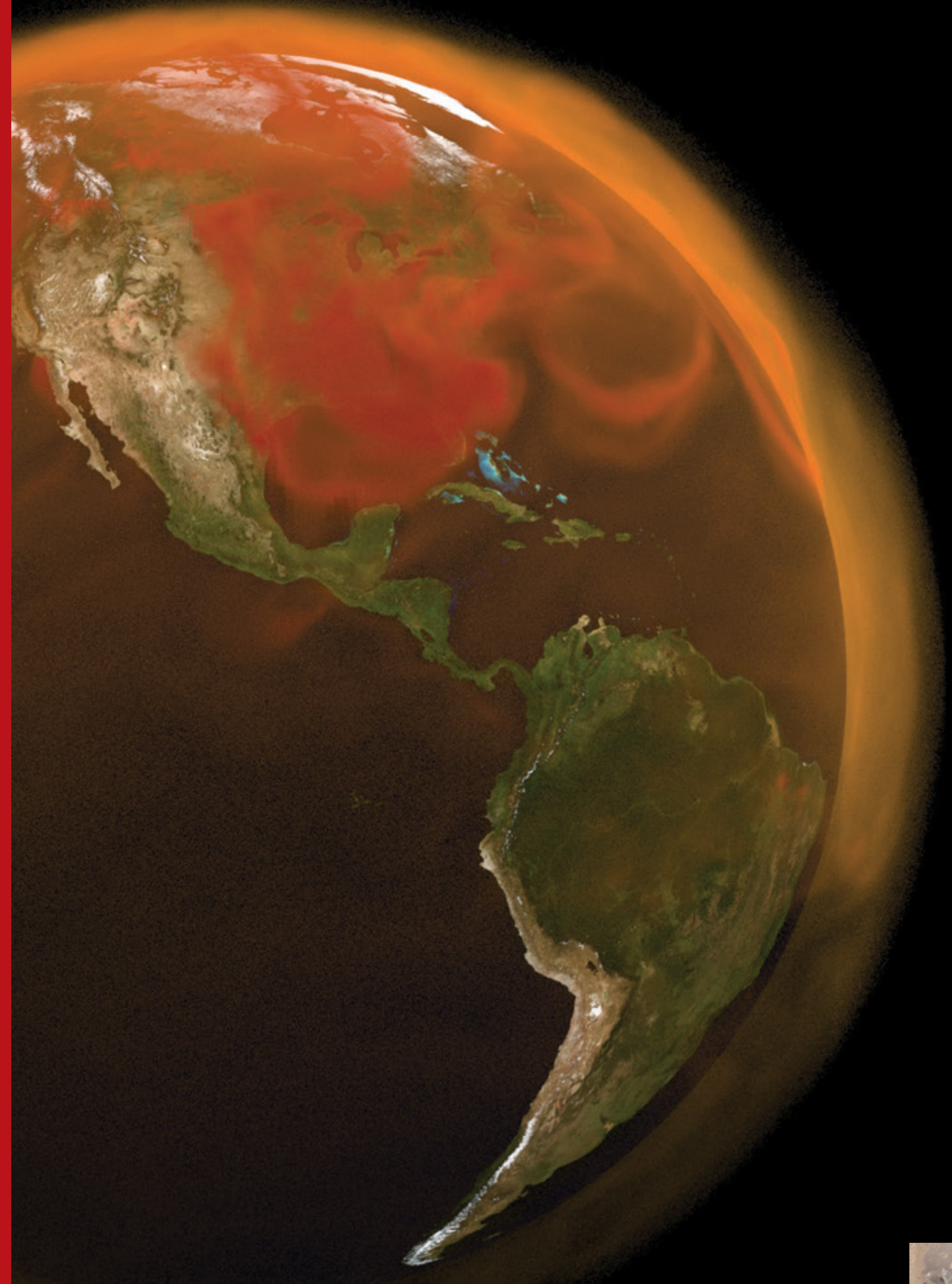


Right: The SPRITE CubeSat primary mirror inside the ALD coating facility at MDL. The primary mirror is 16 × 18 × 5 cm and is the largest optic coated to date in this chamber.

2025-2040
LAUNCHES

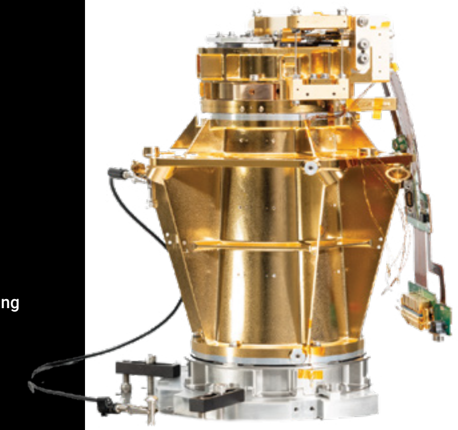
LOOKING BEYOND TOMORROW

To support future NASA missions, MDL is investing in technology maturation and technology readiness advancement. Components are being developed for upcoming high-resolution and ultra-compact spectroscopy instruments for Earth science, while detectors and novel optics are being fabricated for the direct observation of exoplanets and distant moons, as well as for measurements of the abundance of dust and heavy metals in space.



CARBON-I
HIGH-RESOLUTION MAPPING

2025



Right: State-of-the-art Dyson Imaging Spectrometer with MDL grating.

Greenhouse gases are emitted globally, but the precise distribution is unclear because clouds frequently impede measurements of the tropics. The Carbon Investigation (Carbon-I) will use its extraordinarily high resolution to peer through gaps in the clouds and fill in the missing data.

CARBON-I WAS SELECTED BY THE EARTH SYSTEM EXPLORERS PROGRAM FOR A CONCEPT MISSION

Plumes of carbon dioxide in China, detected from space.

Greenhouse gas emissions on Earth are heterogenous, and a full understanding of where they occur requires a complete mapping of emissions globally. Evidence suggests that the tropics have a particularly high concentration of methane emissions; however, dense cloud cover frequently impedes accurate measurements from space that would corroborate this evidence.

To solve this problem, the Carbon-I will use very high spatial resolution absorption spectroscopy to quantify emissions of carbon dioxide, methane, and carbon monoxide globally to a resolution within a city block.

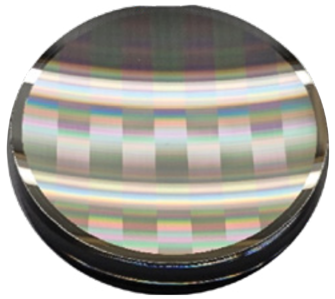
In global mode, Carbon-I will conduct monthly <400 m sampling of land and coastal oceans. By contrast, target mode will act as a magnifying lens, supporting <50 m sampling of key regions spanning over 2 million acres. This resolution is high enough to peer through gaps in clouds over the tropics that are usually no more than 1 km wide.

MDL support has come in the form of a grating, slit, and light trap. Additionally, MDL's Dr. Robert Green and Dr. Andrew Thorpe are providing the mission with calibration support and assistance with imaging spectroscopy, respectively.

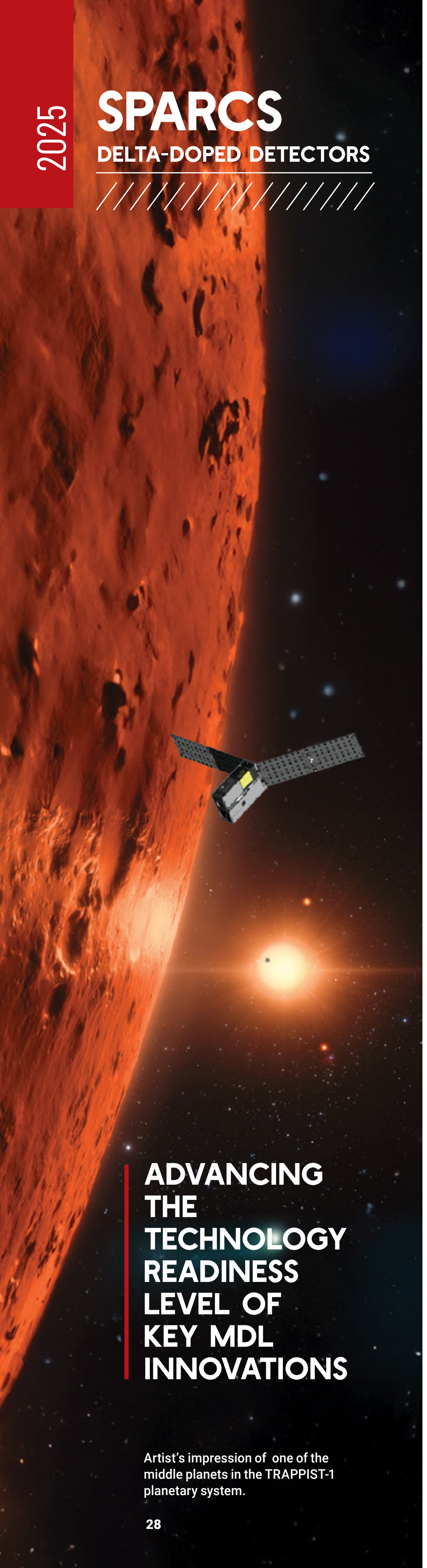
HIGH-RESOLUTION SPECTROSCOPY WILL IDENTIFY GREENHOUSE GAS EMITTERS IN THE TROPICS

Consequently, Carbon-I will collect 1,000 times more data about the tropics than is currently available. The mission will also be able to distinguish between the sources and composition of emissions, whether naturally derived or anthropogenic.

In May 2024, Carbon-I was one of four proposals selected by NASA's Earth System Explorers program for a yearlong concept mission. The program supports PI-led missions that advance the science objectives outlined in NASA's 2017 Decadal Survey for Earth Science and Applications from Space. The Carbon-I team is led by PI Christian Frankenberg at Caltech.



Carbon-I grating.



2025

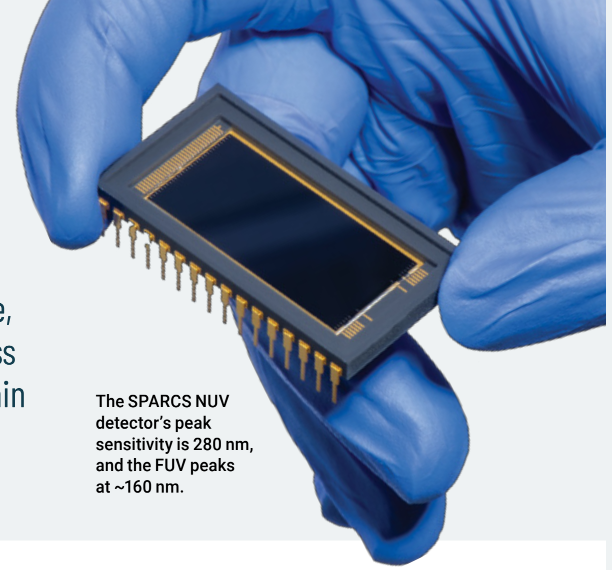
SPARCS

DELTA-DOPED DETECTORS

ADVANCING THE TECHNOLOGY READINESS LEVEL OF KEY MDL INNOVATIONS

Artist's impression of one of the middle planets in the TRAPPIST-1 planetary system.

Within the Milky Way alone, roughly 50 billion low-mass stars are thought to contain at least one small planet within the habitable zone.



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

To help determine whether these small planets could actually harbor life, the Star-Planet Activity Research CubeSat (SPARCS), a space telescope about the size of a cereal box, will observe 20 of these low-mass stars continuously over an extended period of time to establish the total UV flux, including the impact of solar flares on these planets and their atmospheres. Additionally, SPARCS will advance the technology readiness level (TRL) of delta-doped silicon detectors, including both antireflection (AR)-coated and solar-blind UV detectors.

SPARCS is slated to be the first on-orbit demonstration of high-performance delta-doped detectors. As such, SPARCS is an important vehicle for the technology advancements required for the Decadal Survey-recommended next Great Observatory, which includes the development of large-format, high-resolution UV detectors and solar-blind UV detectors. SPARCS will 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 AR coating optimized for the 260-300 nm bandpass. 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.

The SPARCS Camera (SPARCam) collaboration also uses JPL's modular camera electronics. The SPARCam subsystem was delivered to Arizona State University (ASU) in October 2023. Payload assembly, integration, and testing (AIT) began in early 2024, and spacecraft AIT began July 2024.

The project is being developed in collaboration with Prof. Evgenya Shkolnik and her team at ASU and is funded through NASA's Astrophysics Research and Analysis (APRA) program.

MDL contributed the high-performance delta-doped detectors that will be used on the SPARCS telescope.

Sensor board and detector for the near UV channel of the SPARCam for SPARCS.

2026

ARTEMIS III

E-BEAM TECHNOLOGY

Following a series of successful demonstrations, an ultra-compact imaging spectrometer for landed missions to the Moon (UCIS-Moon) will be brought to the lunar surface as part of the Artemis III crewed mission.

ULTRA-COMPACT SPECTROSCOPY'S NEXT STOP IS THE MOON

The Artemis III mission will be the first to send humans to the Moon in more than 50 years and the first ever to send humans to the lunar South Pole. When the mission launches, the UCIS-Moon instrument will be aboard.

UCIS-Moon is a short wavelength infrared (SWIR) Offner imaging spectrometer with a volume of ~55 cm^3 and a weight of only 6 kg. Its small dimensions and low weight will make it possible for an astronaut to operate UCIS-Moon on a tripod on the lunar surface.

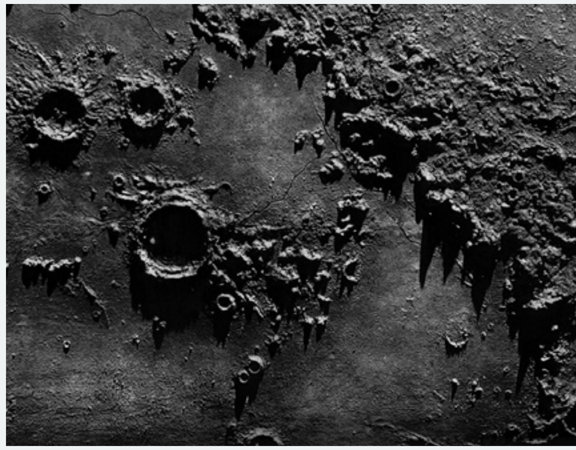
The instrument has a 30-degree field of view, a spatial resolution of millimeters to meters, and a spectral range of 600-3,600 nm. This range will allow UCIS-Moon to detect lunar minerals, hydroxide species, water, and organic compounds.

Astronauts can use UCIS-Moon data to precisely map the composition of the lunar surface, analyze lunar volatiles, and study their changes over time.

UCIS-Moon was developed first under the Maturation of Instruments for Solar System Exploration (MatISSE) program and then under the Development and Advancement of Lunar Instrumentation (DALI) program. It represents three major advancements from its predecessor: an extended spectral range, the ability to withstand harsh lunar conditions (where temperatures can vary by as much as 200 C), and onboard data processing. It is a rugged instrument; even though the lunar surface can reach temperatures as high as 96° C, UCIS-Moon will still be able to return high-quality spectral data.

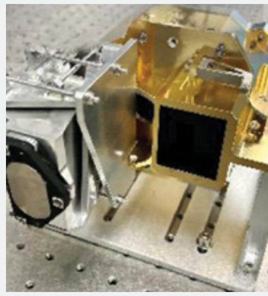
The instrument's uniformity and spectral and spatial response were calibrated and characterized using best practices learned from previous instruments such as the High-resolution Volatiles and Minerals Moon Mapper (HVM^3) and the Mapping Imaging Spectrometer for Europa (MISE).

MDL enabled UCIS-Moon by using its e-beam technology to fabricate the instrument's gratings and slits.



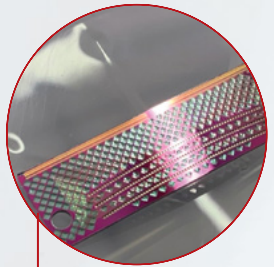
Above: a densely cratered area near the Moon's south pole.

Below: The UCIS-Moon spectrometer and grating.

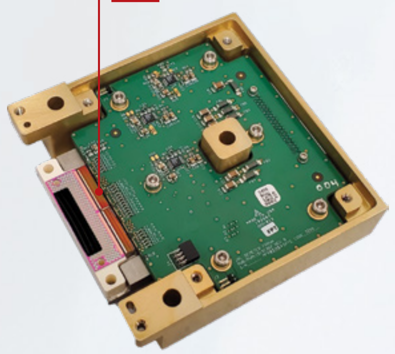


DEMETER

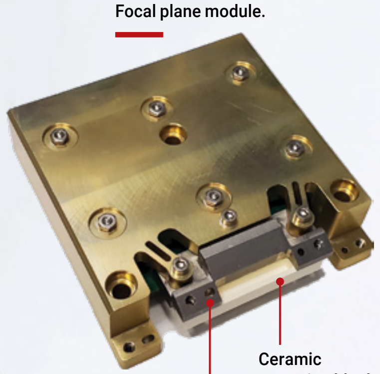
FOCAL PLANE MODULE



Detector chip without gold black.

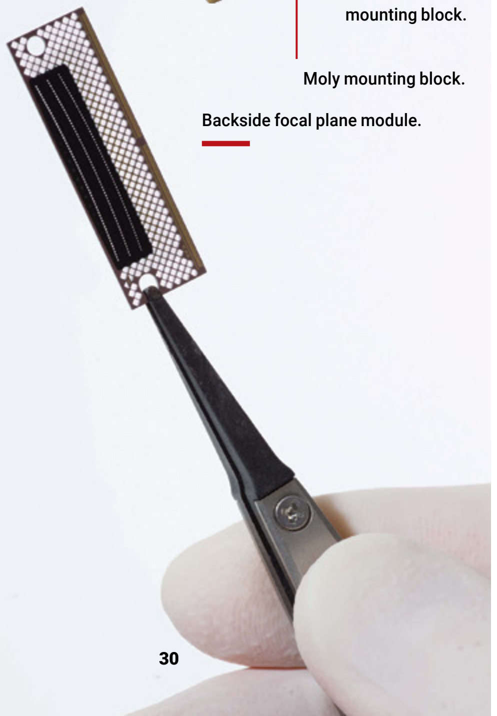


Focal plane module.



Ceramic mounting block.

Moly mounting block.



Backside focal plane module.

The DEMonstrating the Emerging Technology for Measuring the Earth's Radiation (DEMETER) instrument will provide the highest resolution data ever available on the Earth radiation budget (ERB), facilitating a clearer understanding of how ERB drives climate trends and affects local weather patterns.

The ERB is the difference between the amount of radiant energy reaching Earth from the Sun and the amount reflected and emitted from Earth back into space. ERB is an important factor in Earth's climate, both globally and locally, and next-generation spaceborne instruments such as DEMETER can help understand ERB with greater precision and in more detail than ever before.

This radiometric sensor will be built using NovaWurk's "building block" platform along with wide-field angle telescopes. In the heart of the instrument is an MDL focal plane module which includes a custom thermopile detector array and specialized readout integrated circuits suited for the detector array. All these elements result in a smaller, more cost- and energy-efficient instrument compared to the legacy instruments currently flying.

Initially funded by NASA's Earth Science Technology Office (ESTO) Instrument Incubation Program (IIP), DEMETER will use a push broom observation approach, coupled with high spatial resolution (<25 km) to quickly collect data that are tenfold more detailed than any currently available. This high-resolution data will help unravel the association between ERB and climate trends. Importantly, the data will be made available in near-real time, enabling a better understanding of how ERB is related to local weather events.

The ultimate goal is to fly a constellation of DEMETER instruments in low-Earth orbit to facilitate continuous monitoring of ERB globally.

A CONSTELLATION OF INSTRUMENTS MAY ONE DAY PROVIDE GLOBAL INSIGHTS INTO THE RELATIONSHIP BETWEEN ERB AND CLIMATE CHANGE

DEMETER's prototype was built using a modified version of the focal plane module (FPM) developed by MDL for NASA's Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE) mission. The DEMETER instrument may make its first flight in 2027.

Roman Coronagraph fast steering mirror.

CGI

DIFFRACTIVE OPTICS

More than 5,000 exoplanets have been identified in the last 30 years; however, because stars are so much brighter than planets, fewer than 70 exoplanets have been imaged directly. When the Nancy Grace Roman Space Telescope launches, the Coronagraph Instrument (CGI) aboard will help take a crucial step toward greatly increasing the number of exoplanets identified and directly imaged.

The CGI is a technology demonstration that will use advanced techniques to more precisely block the light from a star and reveal the planets that may be orbiting it. Instead of using a static disc to block starlight, the CGI will utilize multiple masks and two small, deformable mirrors driven by thousands of tiny pistons to precisely manipulate incoming starlight and ultimately remove it through destructive interference. Though these undoubtedly add substantial complexity to the instrument, they are also essential for completing its mission.

The CGI exceeded expectations during its space simulation testing and was subsequently sent to NASA's Goddard Space Flight Center for integration into the rest of the observatory.

The CGI is 1,000 times more capable than previous coronagraphs and will be the first advanced coronagraph flown in space. At its maximum capability, it will be able to directly image planets roughly the size of Jupiter orbiting Sun-like stars.

A successful demonstration aboard the Roman Space Telescope will lay the foundation for the Habitable Worlds Observatory, which aims to image at least 25 Earth-like exoplanets during its time in service.

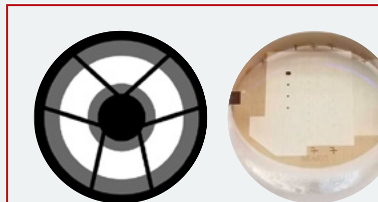
The Roman CGI has relied heavily upon MDL's expertise for its development.

THE CGI WILL ENABLE THE DIRECT OBSERVATION OF EXOPLANETS

MDL contributed the diffractive optics and occulting spots, light trapping surfaces, precision slits, mirror control actuator elements, and coatings, among others.

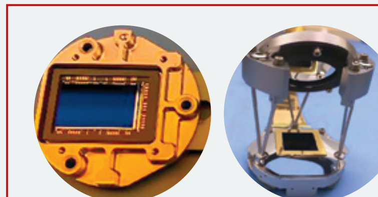
SPC black silicon mask | Mask profile measured using atomic force microscopy

Shaped Pupil Coronagraph (SPC)



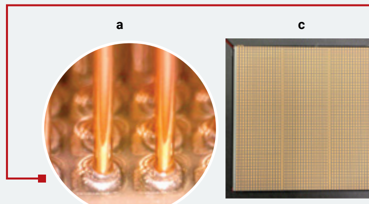
HLC Lyot stop | Focal plane mask

Hybrid Lyot Coronagraph (HLC)



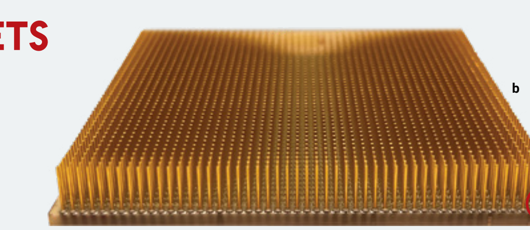
EDU chip | EDU sensor/mirror sub-assembly

Engineering Development Unit (EDU)



Deformable Mirror

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



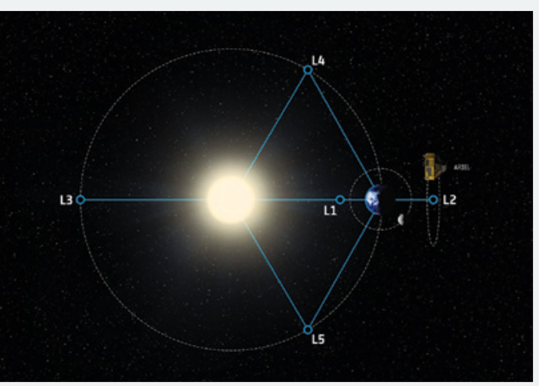
2029

CASE

FLIGHT PACKAGING

A NEW DETECTOR WILL CHARACTERIZE EXOPLANETARY ATMOSPHERES

This artist's concept shows the European Space Agency's ARIEL spacecraft on its way to Lagrange Point 2 (L2) — a gravitationally stable, Sun-centric orbit — where it will be shielded from the Sun and have a clear view of the sky. Credit: ESA/STFC RAL Space/UCL/Europlanet-Science Office.



An artist representation of the chemical makeup of distant extrasolar planets.

The Contribution to ARIEL Spectroscopy of Exoplanets (CASE) is a detector subsystem contribution to an infrared spectrometer instrument for the planned European Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) space telescope.

CASE is being developed by NASA to add scientific capabilities to this European Space Agency (ESA) space telescope, enabling it to observe the chemical composition of the atmospheres of known exoplanets, as well as determine the character of these atmospheres (e.g., whether they are hazy, cloudy, or clear).

The instrument consists of two detectors and associated electronics that are sensitive to light at near-infrared (NIR) wavelengths, as well as visible light. The H2RG detectors and associated electronics, packaged by MDL, are the same that NASA contributed to the ESA's Euclid mission. CASE will be a subsystem of ARIEL's Fine Guidance System (FGS) instrument, which includes three photometric channels (0.5-0.6 µm, 0.6-0.8 µm, and 0.8-1.1 µm) and one grating spectrometer channel covering 1.1-2.1 µm.

In late August 2023, ARIEL successfully completed its Payload Preliminary Design Review (PDR), which included preparing 179 technical documents and addressing 364 questions for an ESA review board. This success put ARIEL at Technology Readiness Level 6, advancing it to Payload Critical Design Review (CDR) and enabling the team to begin manufacturing prototypes.

JPL is leading the engineering and hardware fabrication to adapt the Euclid hardware to ARIEL and its FGS instrument. Hardware testing is being performed at JPL and the Goddard Space Flight Center.

CASE is an Astrophysics Explorers Mission of Opportunity. The Principal Investigator is JPL's Mark Swain. The ARIEL spacecraft, with CASE aboard, is planned to launch in 2029.

ITS DATA WILL SHOW THE ATMOSPHERES' CHEMICAL COMPOSITION AND CHARACTER

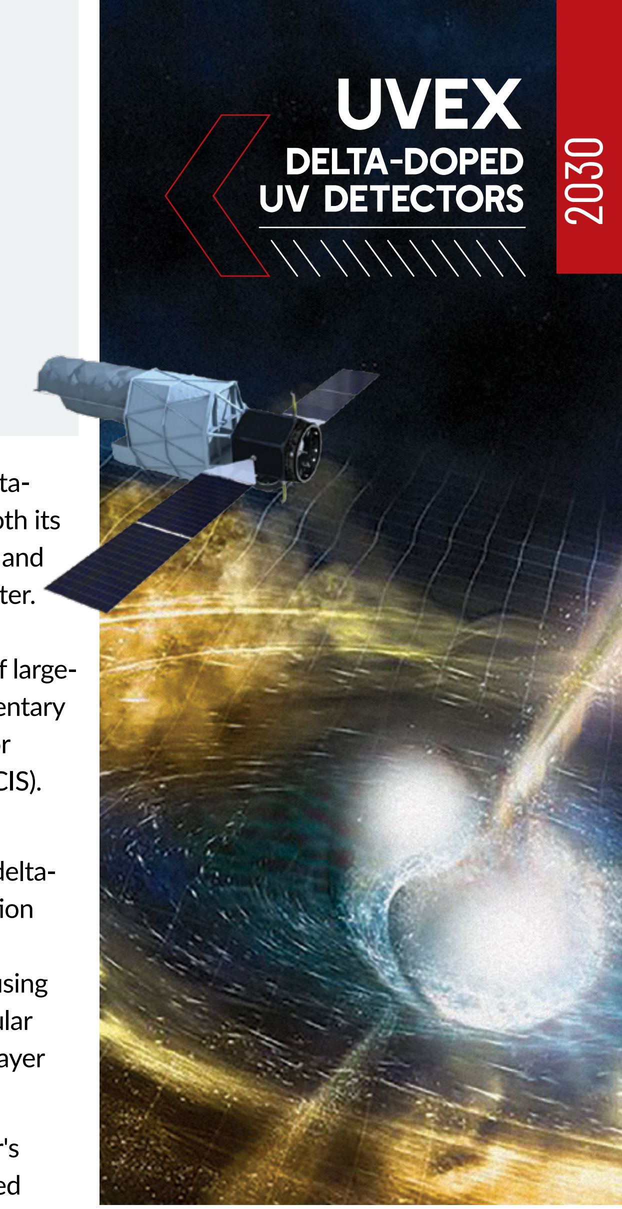
2030

UVEX

DELTA-DOPED UV DETECTORS

The Ultraviolet Explorer (UVEX) is targeted to launch in 2030 as NASA's next Astrophysics Medium-Class Explorer mission.

EXPLORING THE DYNAMIC ULTRAVIOLET UNIVERSE



UVEX will undertake a synoptic survey of the entire sky in the near-UV and far-UV, probing the dynamic universe with a sensitivity more than 50 times better than its predecessor, the Galaxy Evolution Explorer (GALEX). UVEX will also have a powerful broadband spectroscopic capability. It will address fundamental questions from the 2020 Decadal Survey on Astronomy and Astrophysics and study the evolution of low-metallicity, low-mass galaxies.

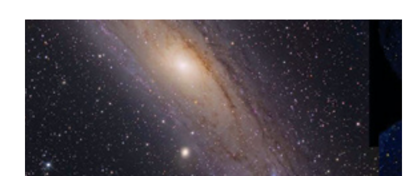
UVEX time-domain surveys will probe the aftermaths of gravitational wave-discovered compact object mergers, discover fast UV transients, and diagnose the early stages of explosive phenomena. With a wide-field, two-band UV imager and long, multi-width slit spectrometer, UVEX is equipped to address key scientific themes identified in "Pathways to Discovery in Astronomy & Astrophysics for the 2020s."

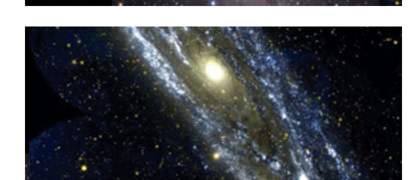
UVEX baselines MDL's delta-doped UV detectors for both its wide-field imaging system and multi-width slit spectrometer. The wide-field imager will include a 3k × 3k mosaic of large-format (4k × 4k) complementary metal-oxide semiconductor (CMOS) imaging sensors (CIS).

The CIS detectors will be optimized for UVEX with delta-doping, custom antireflection coating and UV bandpass filters developed at MDL using techniques such as molecular beam epitaxy and atomic layer deposition.

Similarly, the spectrometer's detector will be delta-doped for UV optimization; bandpass optimization will be achieved with state-of-the-art coating techniques developed at MDL that allow for spatially varying the response of silicon UV detectors.

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

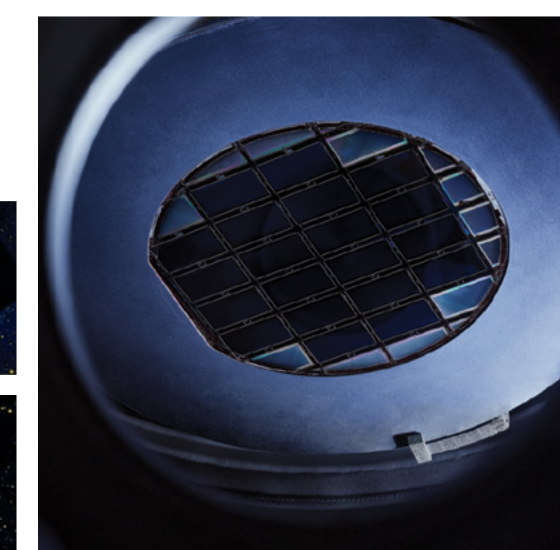




Right: The Andromeda Galaxy (M31) looks distinct in optical (top) and ultraviolet (bottom) wavelengths. UVEX will survey the sky for UV sources, targeting hot binaries in low-mass galaxies near the Milky Way and signs of exploding stars. Credit: [top] Optical: Adam Block/NOAO/AURA/NSF; [bottom] UV: GALEX/JPL/NASA.

Above: An artist's illustration of merging neutron stars shows gravitational waves as a rippling space-time grid, gamma-ray bursts as narrow beams, and glowing clouds of ejected material. Credit: NSF/LIGO/Sonoma State University/A. Simonnet.

Below: A CCD wafer in the molecular beam epitaxy system used for delta doping.

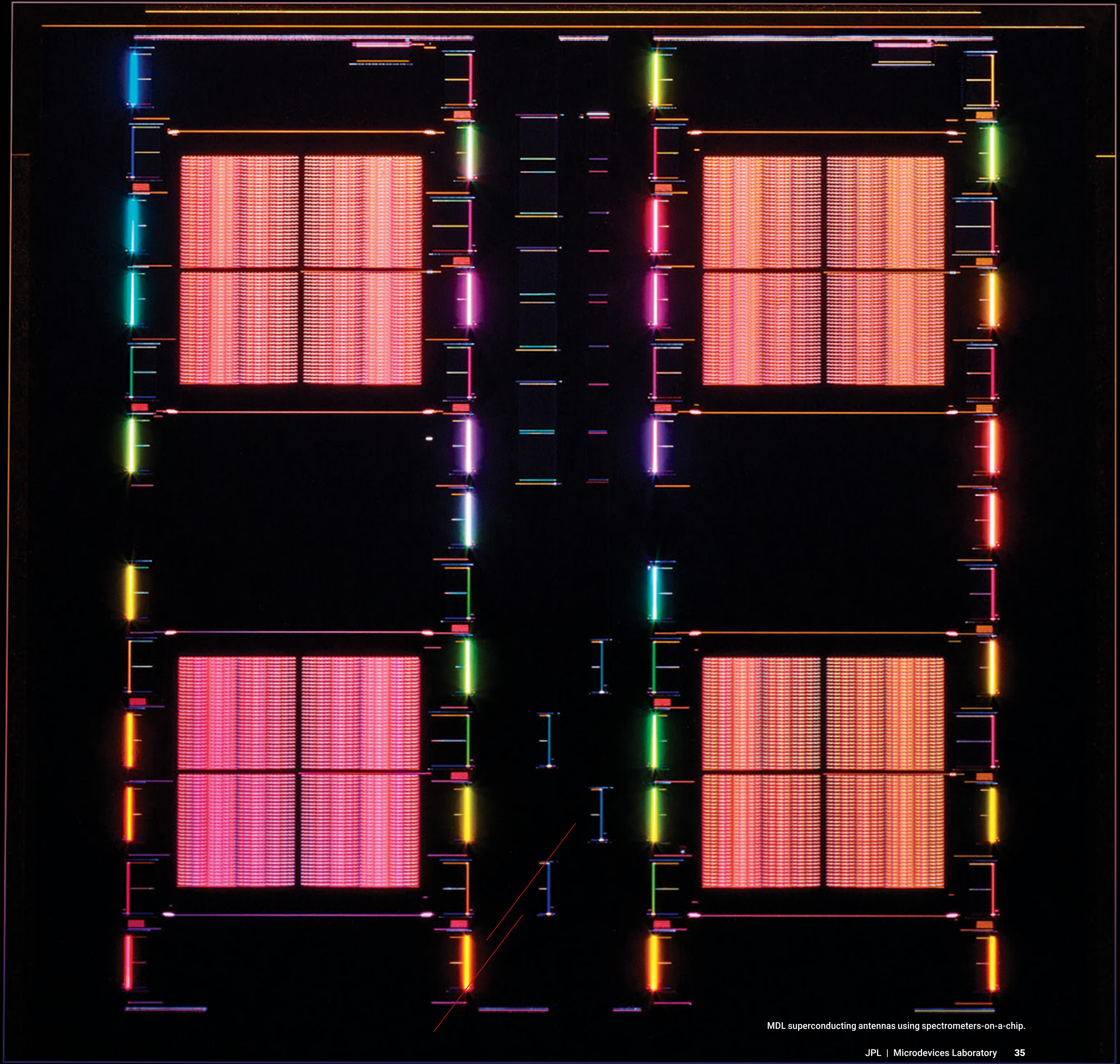


S.2

MDL HIGHLIGHTS

In the long term, the impact of MDL is evaluated by its ability to continuously incorporate novel or even disruptive technologies in space.

New and viable ideas must be identified and incorporated into the current state of the art. As many advances could come from non-space sectors, such sectors must be actively researched for potential ideas.



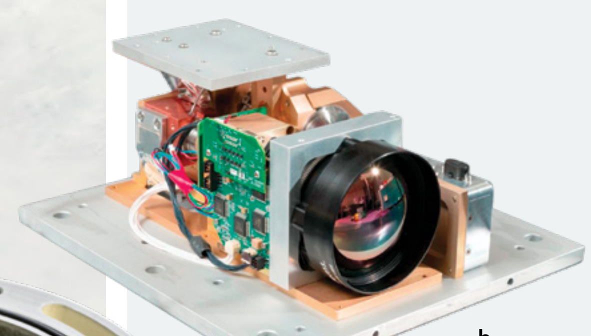
MDL superconducting antennas using spectrometers-on-a-chip.

The HyTI 6U SmallSat just seconds after its deployment from the ISS. The large solar panel in the top right corner belongs to the ISS.

HyTI

MONITORING WATER AND EARTH FROM AIR

The Hyperspectral Thermal Imager (HyTI) aimed to prepare for the future through agricultural remote sensing. Achieving its primary goals would help address food and water security. HyTI was also to predict volcanic eruptions by measuring magmatic gases, which would have helped secure humanity's short- and long-term safety. Its successor is already being prepared for launch in late 2025.



(a) 24-µm pixel pitch, 640 × 512 pixel LWIR HOT-BIRD FPA; (b) 2U HyTI instrument based on HOT-BIRD FPA.

HyTI was a 6U CubeSat designed and built as a technology demonstration to enable the next generation of high spatial, spectral (30 spectral channels from 8.0-10.7 µm) and temporal resolution thermal infrared (TIR) imagery acquisition from low Earth orbit (LEO).

Its primary objectives were to monitor global hydrological cycles and water resources and to develop a detailed understanding of water movement, distribution, availability, and variability over time. An associated goal was the measurement of land surface dynamics by monitoring the continuous variability of land surface temperature (LST). While LEO hyperspectral TIR observations would enable detailed measurements of both hydrological and LST variability, the focus was on enabling agricultural remote sensing.

HyTI was designed to investigate three global food and water security issues: mapping both irrigated and rainfed croplands, determining the water use of major world crops, and establishing the crop water productivity ("crop per drop") of major world crops.

An additional goal for HyTI was to help predict volcanic eruptions. Magmatic gases emitted by volcanoes serve as an early warning of impending eruptions.

Quantifying the low-intensity gas emissions that characterize these pre-eruptive states requires high spatial and spectral resolution long-wave infrared (LWIR) measurements to allow both the detection and quantification of gas fluxes, thus expanding current knowledge of how these fluxes vary in time. Hyperspectral imaging with high spatial resolution in the LWIR has not yet been achieved from space in quantifying magmatic gas emission from volcanoes.

HyTI was funded by the NASA Earth Science Technology Office (ESTO) In-space Validation of Earth Science Technologies (InVEST-17) program. It was developed at JPL based on the breakthrough high operating temperature-barrier infrared detector (HOT-BIRD) focal plane array (FPA) technology and a compact Fabry Perot spectrometer (FPS) supplied by the University of Hawai'i.

The HyTI instrument consisted of a 640 × 512-pixel HOT-BIRD FPA, the FPS, an AIM SF-70 cryocooler, Creare cryocooler drive electronics, FPA drive electronics and commercial off the shelf (COTS) optics.

Its long-wavelength FPA operated at 70K and was radiation tolerant up to 40 Krads with its COTS readout integrated circuit. Its size, weight, and power (SWaP) were 2U, 3 kg, and 30 W, respectively. Two HyTI Engineering Detector Units (EDUs) were delivered to the University of Hawai'i for testing and integration with the ISISPACE 6U satellite bus.

HyTI was launched on SpaceX CRS-30 to the International Space Station. The launch was provided by NASA's CubeSat Launch initiative (CSLI), which provides low-cost access to space for U.S. educational institutions and NASA centers. In a 430 km orbit, the HyTI instrument had a ground sampling resolution of 60 m for 25 spectral samples in the 8.0-10.7 µm wavelength range, with narrow-band noise equivalent variation in temperature (NEdT) of less than 150 mK.

Such advanced TIR spectral resolution would be better able to quantify the path concentration of volcanic SO_2 in the atmosphere and estimate

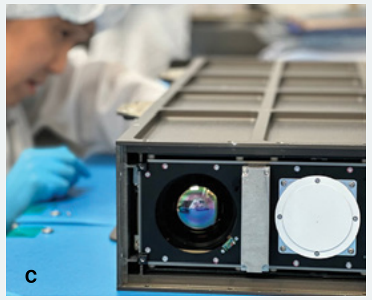
MDL'S CONTRIBUTIONS TO HYTI AND HYTI-2 INCLUDE ITS LWIR HOT-BIRD FPA AND ITS DEWAR COOLER ASSEMBLY

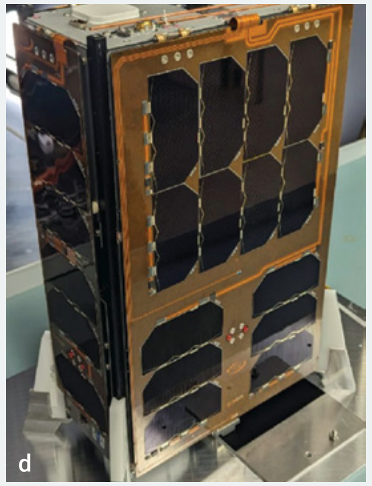
the outgoing long-wave radiation and fluxes of sensible heat, latent heat, and conduction into or out of the soil. Unfortunately, the HyTI SmallSat became a victim of the G5 geomagnetic storm that occurred from May 10-11, 2024.

However, plans are currently underway for a future constellation of 25-30 HyTI satellites that could one day monitor Earth's volcanoes for signs of impending eruption and map soil moisture for crop management at a lower cost than a single conventional satellite. To that end, HyTI's successor, HyTI-2, is already being developed.

The FPAs for HyTI-2 have been delivered, and the team is working diligently to complete assembly in time for a scheduled launch in October 2025 on a 16U Orion Space Solutions SmallSat. HyTI-2 will cover the full long-wave infrared spectrum from 8-12 µm, beyond HyTI's original range.

Investigating how water is used in agriculture.





(c) HyTI 6U SmallSat; (d) ISISPACE 6U SmallSat, which could deliver 60 W peak power and a pointing accuracy of 0.1 degree; (e) SpaceX CRS-30 launch on March 21, 2024.

EYES ON EARTH'S THERMOSTAT

The Arctic modulates Earth's temperature, venting excess heat from the tropics. The Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE) mission is the first to systematically measure the heat released from Earth's poles, giving a precise look into a key regulator of climate change.

THIS TWO-CUBESAT MISSION WILL EXPLORE HOW A WARMING WORLD WILL AFFECT SEA ICE LOSS, ICE SHEET MELT, AND SEA LEVEL RISE

Although Earth as a whole is warming, the Arctic, a key modulator of Earth's temperature, is heating up the fastest, and the reasons why are still poorly understood.

More than half of the heat emitted from the Arctic occurs at wavelengths in the far-infrared (FIR, >15 µm) that have never been systematically measured, so there is still a limited understanding of the spatiotemporal variability in the heat emitted from these regions. Without this information, models of climate change are incomplete.

The PREFIRE mission is filling this gap by putting two CubeSats into distinct polar low-Earth orbits that allows them to take frequent measurements of FIR radiation at the poles, allowing the characterization of these emission patterns on the order of hours to months.

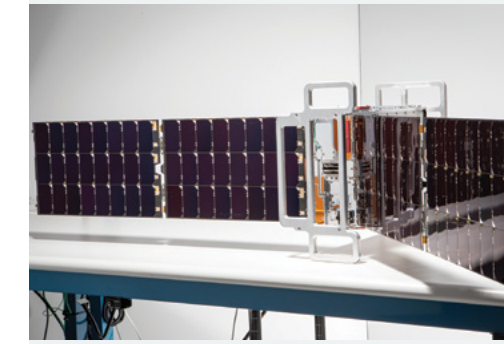
The data will support a clearer understanding of when and where Earth's poles emit FIR radiation, as well as how atmospheric water vapor and clouds influence the amount of radiation that escapes into space. The combination of spectral range (5-45 µm) and spatial resolution make this mission the first of its kind.

The information obtained will yield insights into patterns of Arctic warming, ice sheet melting, sea level rise, cloud cover and surface conditions. Ultimately, the data will help create quantitative models of the feedback between Earth's surface and atmosphere that is thought to amplify the effects of climate change. These more-robust models of climate change will help humanity better prepare for its effects.

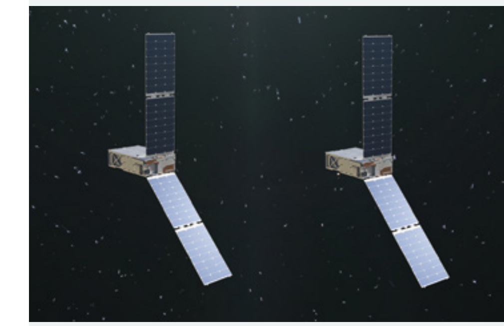
PREFIRE emerged from a close collaboration between scientists and technologists, co-evolving the mission idea based on the available technology and potential technology enhancements to help support the mission concept.

MDL technologists designed and delivered a custom thermopile detector array of 64 pixels × 8 channels that is the heart of the CubeSats' focal plane modules (FPMs). The center of the array is coated with gold black, which provides almost perfect optical efficiency across the wavelengths that PREFIRE measures, and each pixel has freestanding absorbers with four support beams holding the absorber to the substrate. Bi-Te (n-type) and Sb-Te (p-type) thermoelectric wires generate a voltage proportional to the incoming power.

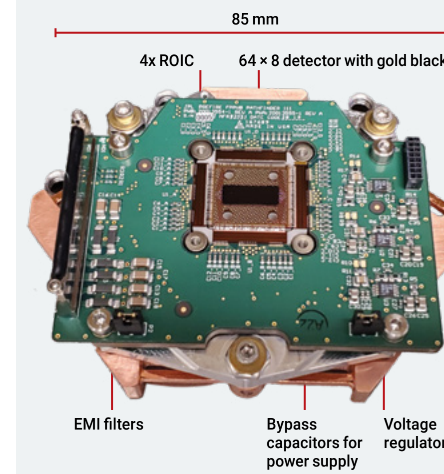
(a) PREFIRE's array has a format of 64 × 8. (b) Each pixel features a suspended silicon nitride absorber coated with gold black and held by four support beams. (c) Bi-Sb-Te thermoelectric wires are patterned on the support beams and act as a thermometer sensing power coupling into the absorber.



An image of the PREFIRE CubeSat. Credit: Blue Canyon Technologies.

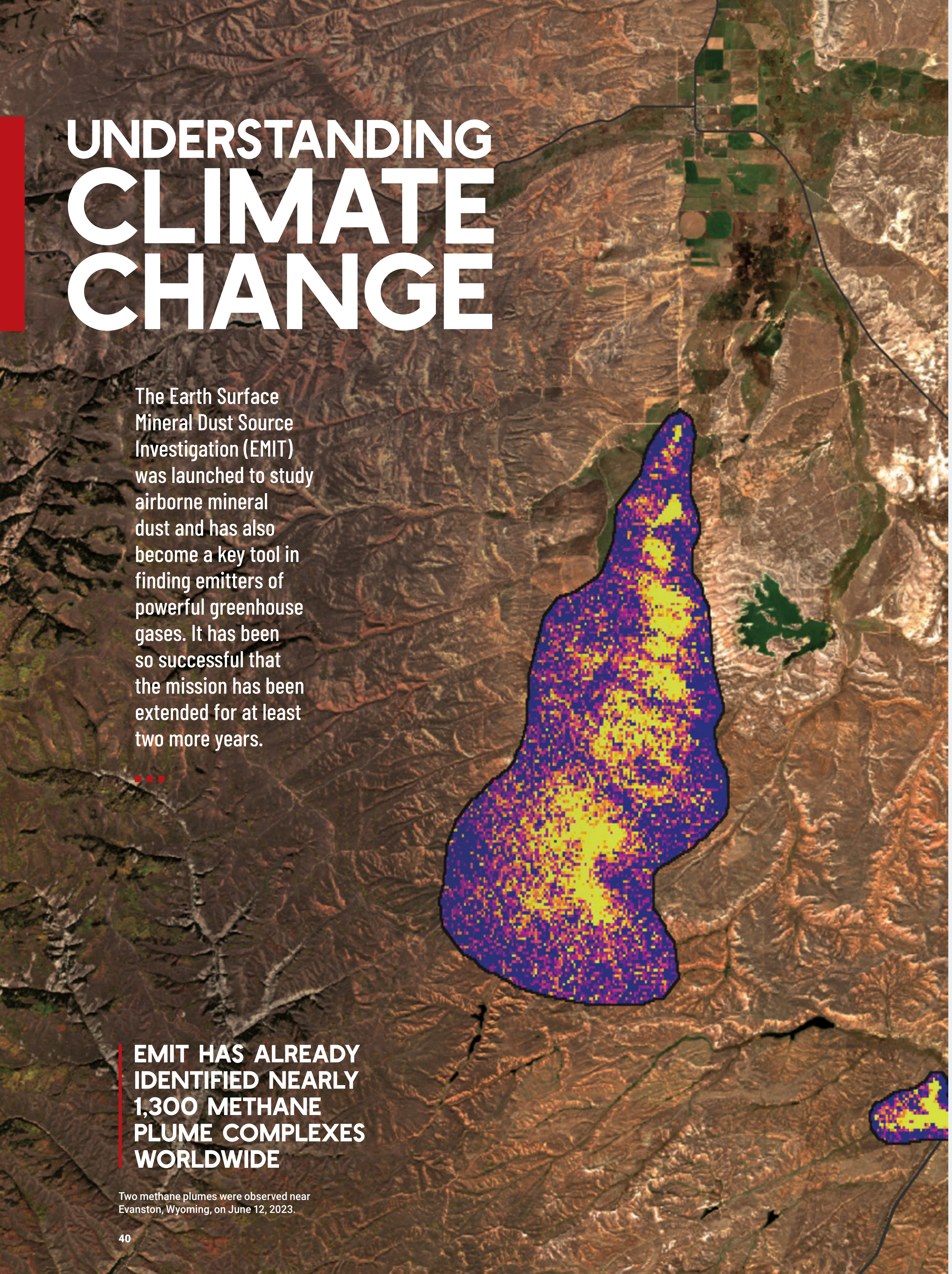


Two CubeSats will orbit near the poles, providing multiple observations per day.



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.

PREFIRE WILL HELP US UNDERSTAND HOW MUCH OF EARTH'S HEAT IS LOST TO SPACE FROM THE ARCTIC AND ANTARCTICA



UNDERSTANDING CLIMATE CHANGE

The Earth Surface Mineral Dust Source Investigation (EMIT) was launched to study airborne mineral dust and has also become a key tool in finding emitters of powerful greenhouse gases. It has been so successful that the mission has been extended for at least two more years.

EMIT HAS ALREADY IDENTIFIED NEARLY 1,300 METHANE PLUME COMPLEXES WORLDWIDE

Two methane plumes were observed near Evanston, Wyoming, on June 12, 2023.

Carbon dioxide and methane are critical drivers of climate change. Although carbon dioxide remains in the atmosphere for centuries and thus exerts long-term effects, methane traps as much as 80 times more heat than carbon dioxide does, making it a much more potent greenhouse gas. The good news is that atmospheric methane begins to break down much more quickly, after only 7-12 years, so reducing methane emissions will have a much faster impact on climate change. To help identify sources of methane and carbon dioxide emissions, the EMIT instrument orbits Earth mounted on the International Space Station (ISS), capturing 50-square-mile “scenes” of the planet’s surface.

EMIT includes an advanced two-mirror telescope and a high-optical-throughput F/1.8 Dyson imaging spectrometer, and it can measure from the visible to the short-wave infrared (SWIR) portions of the electromagnetic spectrum (380-2,500 nm), which includes the region where both carbon dioxide and methane have their spectral fingerprints (1,900-2,500 nm).

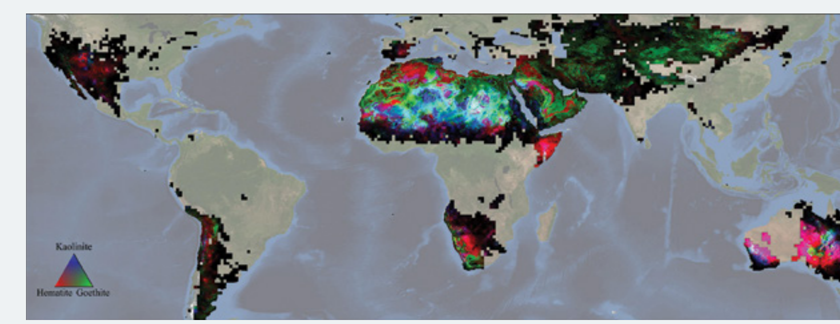
To date, EMIT has collected more than 55,000 scenes and billions of data points, which have allowed the team to identify nearly 1,300 methane plumes worldwide. Additionally, the EMIT team is fostering transparency by making their data publicly available on a NASA portal that allows anyone to see where methane and carbon dioxide are being emitted.

While airborne observations of emissions can allow more detail, EMIT can find 60-85% of the plumes detected by airborne campaigns and identify small methane plumes (hundreds of pounds per hour). It can also locate emissions in places that aircraft cannot reach. For example, EMIT found a small methane plume emitting just less than 1,000 pounds of methane per hour in a remote part of Libya.

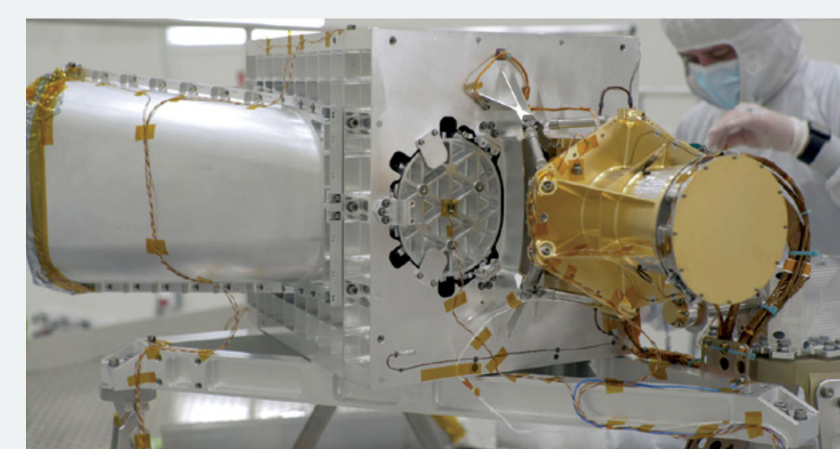
The EMIT mission has been so successful that it has been extended for at least another two years as part of the Research Opportunities in Space and Earth Sciences (ROSES) funding program. The extended mission will support 16 additional studies,

SCIENCE MEASUREMENTS HELP US UNDERSTAND GREENHOUSE GASES AND RESULTS

including one that will independently validate EMIT’s findings and others on topics ranging from the dust produced by drying ephemeral lakes to the floral composition of desert blooms to the success of agricultural conservation practices. Some of the funded studies will also help lay the groundwork for future spaceborne research, ensuring that EMIT’s legacy lives on long after the instrument itself is decommissioned.



The EMIT mission produces maps of arid region surface minerals.



EMIT incorporates multiple advanced new technologies. Its Dyson spectrometer optical layout provides exceptionally high photon throughput, meaning the optics maximize the light reaching the detector. The detector array uses new custom coatings to maximize sensitivity over the full EMIT wavelength range.

STUDYING WATER ON THE MOON

Although the Moon has water, little is known about where it is located, the form it takes, and how that form changes over time. The Lunar Trailblazer mission, which includes the High-resolution Volatiles and Minerals Moon Mapper (HVM^3), will fill this knowledge gap.

AN IMAGING SPECTROMETER ABOARD WILL HELP MAP LUNAR WATER DISTRIBUTION

Lunar Trailblazer's HVM^3 Imaging Spectrometer.

Convex grating for HVM^3.

The first confirmation of water on the Moon outside of its permanently shadowed areas occurred in 2020, and the next critical observations will include that water's location and form, as well as the characteristics of the lunar water cycle. The important data retrieved from these observations may affect future crewed lunar missions and eventual lunar settlements.

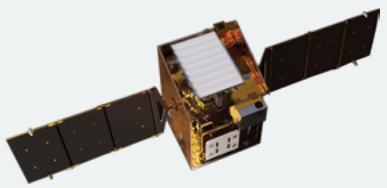
The Lunar Trailblazer mission will study the Moon's water using two instruments: the Lunar Thermal Mapper (LTM), developed by the University of Oxford, and the MDL-supported High-resolution Volatiles and HVM^3, an Offner imaging spectrometer designed to detect water on the lunar surface.

The Lunar Trailblazer spacecraft weighs only about 200 kg and will be less than 3.5 m wide in operation, including its solar panels. Its HVM^3 instrument will detect light in the 600-3,600 nm range with 10 nm spectral resolution and ~100 m spatial resolution. Importantly, it was designed to be very sensitive to light, so it will be able to detect traces of water in the Moon's permanently shadowed regions and distinguish between water's different physical states. It will also be able to detect carbon dioxide, methane, ammonia, and other species.

Thus, HVM^3 data will support mapping lunar water and other species, characterizing the lunar water cycle, identifying the physical state of water in a given location, and showing whether that state changes as exposure to sunlight changes. Lunar Trailblazer was selected for NASA funding in 2019 through its Small Innovative Missions for Planetary Exploration (SIMPLEx) program, which supports high-risk, low-budget missions that explore other planets, moons, and asteroids.

HVM^3 was delivered in 2022 and underwent a successful test of alignment and calibration at temperatures in which it will operate, and it was integrated into the Lunar Trailblazer SmallSat spacecraft shortly thereafter.

The science resulting from the mission will help answer fundamental questions raised in the two most recent Decadal Surveys for Planetary Science, including "How are volatiles distributed and transported on the Moon?" and "What are the inventories and origin of water on airless bodies?"



MDL FABRICATED THE GRATINGS, SLIT, AND ZERO-ORDER LIGHT TRAP FOR LUNAR TRAILBLAZER'S HVM^3 INSTRUMENT

EXPLORING GALACTIC EVOLUTION

Many factors, such as gas, dust, radiation, and massive stars, affect how galaxies change over time. The Supernova Remnants and Proxies for Re-Ionization Testbed Experiment (SPRITE) CubeSat will observe these phenomena in the ultraviolet (UV) portion of the spectrum, providing new data on galactic evolution while demonstrating the coating technology that will be used on future NASA flagship missions.

The SPRITE CubeSat is a NASA-funded mission led by Brian Fleming and his team at the University of Colorado Boulder with significant contributions by JPL. SPRITE is designed to study how gas and dust are processed in galaxies by star formation and supernovae and how energetic ionizing radiation is transported from hot stars into the intergalactic medium between galaxies. The mission will observe ionizing radiation escape from low-redshift star-forming galaxies and explore the internal processes that shape galaxy evolution.

SPRITE will carry out two scientific surveys over a one-year mission. First, a mapping survey of star-forming regions and supernova remnants in the Milky Way and the Magellanic Clouds will assess the impact of massive stars on galaxy evolution. The second survey will observe the ionizing radiation spectrum of 100 galaxies in the 0.16-0.5 redshift range as proxies for galaxies at the Epoch of Reionization.

SPRITE operates in the windowless vacuum UV spanning 100–175 nm. SPRITE's innovative optical design allows for the testing and advancement of state-of-the-art mirror coating technologies in preparation for future, larger missions. One such technology is MDL's thin-film protective coatings for reflective optics, developed using atomic layer deposition (ALD) which has been shown to improve the environmental stability of traditional coatings based on physical vapor deposition (PVD) processes. The improved performance is because of the ALD MgF_2 layer; it is uniform and dense enough to provide a moisture barrier for the underlying lithium fluoride (LiF)

MDL FOCUSES ON DEVELOPING NEW UV MIRROR COATING PROCESSES

but thin enough to minimize additional optical absorption loss. This process was first validated on mirrors for the sounding rocket program Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanets (SISTINE) in an initial test flight in 2019. SPRITE's primary mirror, fold mirror, and grating will include ultra-thin (a few nanometers), protective capping layer coatings deposited at MDL.

The SPRITE demonstration of advanced UV coatings will be critical to the development of a future flagship mission recommended by the Decadal Survey with capabilities from the infrared to optical to the UV to support all three of its main themes. Now called the "Habitable Worlds Observatory" (HWO), this mission will have objectives ranging from astrophysics to exoplanet detection and investigation. It will require advances in mirror coating performance, stability, and uniformity.

In addition to the work on SPRITE and other missions — such as Aspera, a Pioneers SmallSat mission — a JPL team is leading a NASA Strategic Astrophysics Technology program that will advance the readiness level of meter-class protected aluminum mirror coatings fabricated using ALD.

BALLOONING INTEREST IN STAR FORMATION

Suspended from a football-stadium-sized balloon, the Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths (ASTHROS) observatory will use high-resolution far-infrared imaging to study how stars form.

Among the most enigmatic questions in astronomy is how the formation of one star affects the formation of stars nearby, a process called stellar feedback. Stellar feedback has played a critical role in the evolution of galaxies throughout the universe's history. Without it, the available gas and dust in galaxies like our own would have coalesced into stars long ago, and no new star formation would take place.

Key tracers of star formation emit in the far-infrared at frequencies between 1.4-4.7 THz. These signals are blocked by water vapor in Earth's atmosphere and are only observable from space or near space. The ASTHROS observatory will observe ionized nitrogen emissions in the 1.4-2.5 range from an altitude of 120,000 feet. It will be launched from NASA's Long Duration Balloon Facility in Antarctica.

ASTHROS benefits from MDL's core competencies in superconducting hot electron bolometer (HEB) submillimeter-wave technology and high-power broadband Schottky-diode-based frequency multiplied local oscillator submillimeter-wave sources.

It also includes a 2.5 m antenna to collect far-infrared light. The new generation of JPL terahertz local oscillators can generate substantial power to drive the HEB mixers with much lower power consumption than their predecessors. ASTHROS also features a 4 K electrical cryocooler, so it does not rely on liquid helium aboard, allowing extended mission lifetimes and thus a larger science return.

When it is launched, ASTHROS will spend its 3-4 week flight focusing on a selection of star-forming regions in our galaxy and nearby galaxies. To investigate stellar feedback, ASTHROS will use a technique called high-spectral-resolution spectrometry, which allows scientists to identify specific chemical elements in gas and dust clouds and to measure precisely the density and dynamics of those elements.

ASTHROS will be the first mission to conduct high-spectral-resolution spectrometry in a few specific wavelengths of light and identify two specific nitrogen ions that are formed by the processes that drive stellar feedback. This strategy will enable astronomers to create 3D maps of star-forming regions, as well as the density and movement of the gas in them, to learn about the influence of stellar feedback.

The ASTHROS mission's primary mirror is one of the largest to ever fly on a high-altitude balloon.

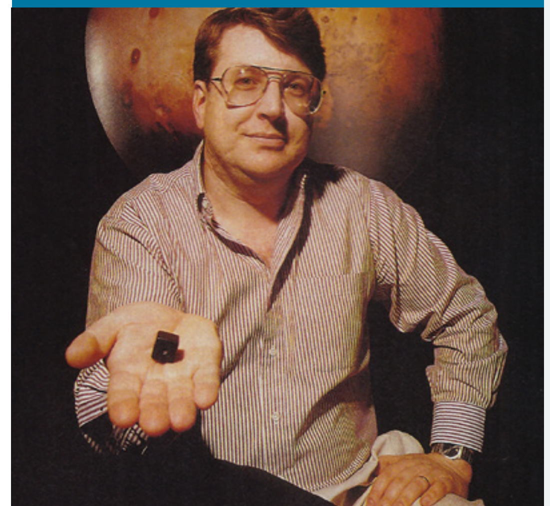
FROM 120,000 FEET ABOVE EARTH, A NEW OBSERVATORY WILL UNCOVER DATA ON STAR FORMATION

S.3

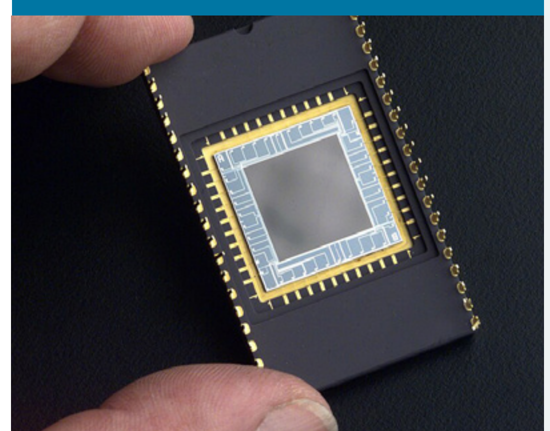
MDL SPIN-OFFS

HOW INNOVATION GROWS BEYOND THE ORIGINAL

Some innovations that have greatly benefited humanity began as NASA projects. Several of these innovations originated at MDL, with a few highlighted in the following section.



Eric Fossum displays a "camera-on-a-chip" CMOS image sensor.



A specially developed CCD in a wire-bonded package used for ultraviolet imaging.

CMOS technology, which grew out of space imaging research at JPL, has made dental X-rays safer, cheaper and easier to process.
Credit: Courtesy of Schick by Sirona.

CMOS

A TECHNOLOGY DEVELOPED AT MDL ENABLES IMAGES OF DISTANT GALAXIES, DENTAL X-RAYS, AND EVERYTHING IN BETWEEN

NASA has always had an interest in capturing high-quality images, and in the 1980s, much of the effort around improving image acquisition was focused on charge-coupled devices (CCDs).

CCDs work by passing a light-generated charge from one pixel to the next in an array on a chip, and once the charge reaches the corner of the chip, it is amplified and recorded. But in the 1990s, under a new faster, better, cheaper approach, newly hired MDL engineer Eric Fossum realized that CCDs could be improved through complementary metal oxide semiconductor (CMOS) technology. This technology relies on microelectronic transistors that are themselves amplifiers and thus can amplify their own signal. CMOS had been critical to computer circuitry for decades prior and had previously been explored for image capture, but technology advances between the 1960s and 1990s helped Fossum create a truly revolutionary invention.

With CMOS, each pixel contains a mini CCD to transfer charges internally and an amplifier that reduces readout noise compared with earlier CMOS sensors. The presence of this amplifier makes the pixel an active pixel sensor (APS). Taking advantage of established CMOS manufacturing processes, Fossum and his team were able to integrate almost all other camera electronics onto a single chip, thus creating the "camera on a chip."

The "camera on a chip" technology was more cost effective to make because it relied on existing fabrication processes, allowed for greater miniaturization than had previously been possible, permitted on-chip programming, and required 99% less power than earlier CCDs.

To commercialize CMOS-APS technology, in 1995, Fossum and his colleagues founded Photobit, a company with an exclusive technology license from Caltech. One of Photobit's first clients was Schick Technologies, a company specializing in dental imaging technology. Schick, now a subsidiary of Sirona Dental, had entered into a Technology Cooperation Agreement (TCA) with JPL in 1994 to help advance the commercialization of CMOS technology. They wanted to replace the traditional X-rays used in dental imaging with digital technology, and they believed that CMOS image sensors would be the way to make that happen. Through collaboration with Schick, Fossum and his team adapted CMOS technology for dental imaging. When Photobit was founded, Schick obtained an exclusive sublicense to use CMOS for dental imaging.

Photobit was eventually sold to Micron Technology, who in turn spun the business into a company called Aptina that was later purchased by ON Semiconductor. When Photobit was first sold, the original patents returned to Caltech, and the technology has since been licensed to companies such as Sony and Samsung. These and other companies have pushed the applications of CMOS-APS far beyond dental imaging. Well-known products, such as GoPro cameras, rely on the IT, as do other devices, such as "pill cameras" that facilitate noninvasive endoscopies.

Nearly all of the 5 billion CMOS cameras made every year, including those in smartphones, rely on Fossum's inventions. Clearly, the "camera on a chip" has had a profound global impact.

The "camera on a chip" was such a revolutionary invention that in 2017, Fossum was one of four who received the world's most prestigious engineering award, the Queen Elizabeth Prize, for CMOS technology. The award recognizes "bold, groundbreaking engineering innovation which is of global benefit to humanity," and CMOS technology certainly fits that description. Over their 30 years of existence, CMOS-APS image sensors have truly become an indispensable tool of modern life.

Aptina Imaging Corporation's 10-megapixel complementary metal-oxide semiconductor sensor is the first such device for point-and-shoot cameras.

A HOT WAY TO SEE HEAT

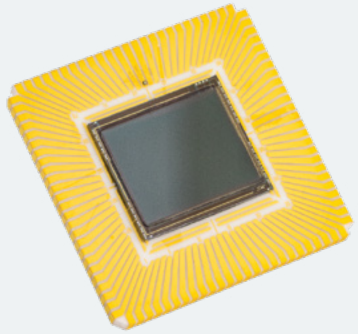
A lot happens in the infrared (IR, 13-12 µm) part of the spectrum, but the materials traditionally used to detect IR wavelengths pose challenges. High operating temperature-barrier infrared detectors (HOT-BIRDs) enable cost-effective IR sensing in a technology that has now been used in satellite observations of Earth and multiple commercial applications.

Handheld mid-wavelength infrared HOT-BIRD camera.

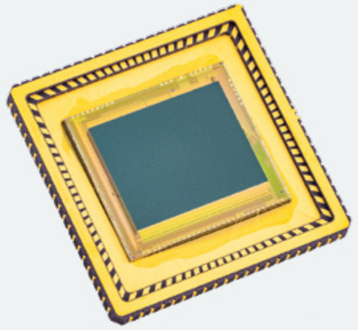
The HOT-BIRD Team: a photo from a visible light camera (top) and an infrared image taken with a HOT-BIRD camera (bottom).

HOT BIRD

Much important information can be gathered from IR observations. These wavelengths are the thermal part of the spectrum and thus can be used to measure land and sea temperatures and detect forest fires, among many other applications.



Picture of a HOT-BIRD FPA, which enabled the compact 2U HyTI instrument for a 6U Smallsat.



HyTI FPA mounted on a lead-less chip carrier (LCC) for radiometric testing.

However, the materials needed to detect these wavelengths pose challenges. Some, such as mercury cadmium telluride (HgCdTe or MCT), are highly adjustable but difficult to work with. Others, such as indium antimonide (InSb), are much easier to work with but lack wavelength versatility. In all cases, detectors that use these materials need to be operated at extremely low temperatures (80 K) to function properly.

To address these challenges, in 2010, MDL scientists David Ting, Alexander Soibel, Sir Rafol, Cory Hill, Sam Keo, Arezou Khoshakhlagh, Brian Pepper, and Sarath Gunapala invented HOT-BIRD, which combines the best qualities of traditional IR detector materials into a more cost-effective detector that can operate at temperatures excess of 150 K. HOT-BIRD focal plane array (FPA) technology covers a wide spectral range spanning from 1-16 µm. The HOT InAs and InAsSb type-II strained layer superlattice (SLS)-BIRD is a key breakthrough in the field of IR detectors and FPAs.

Mid-wavelength IR (MWIR) SLS-BIRD FPAs offer the same high uniformity, operability, manufacturability, and affordability advantages as traditional InSb. However, their ability to operate at significantly higher temperatures (150 K vs. 80 K for InSb) reduces the size, weight, and power demands on cryocoolers.

Moreover, while InSb has a fixed cutoff wavelength (~5.4 µm), HOT-BIRD offers a continuous adjustable cutoff wavelength ranging from ~1 µm to >16 µm and is therefore also suitable for long wavelength (LW) and dual-band (e.g., MW-LW) FPA implementations. In addition, InAs/InAsSb SLS-BIRD FPAs have good temporal stability, which eliminates the need for frequent recalibration.

As such, the SLS-BIRD FPA is an enabling technology for SmallSat thermal IR imaging/hyperspectral imaging applications, where size, weight, power and cost are primary concerns.

MDL'S HOT-BIRD TECHNOLOGY COMBINES THE BEST QUALITIES OF INFRARED DETECTOR MATERIALS

SLS-BIRD technology was selected for use on the Hyperspectral Thermal Imager (HyTI) space mission by NASA's In-space Validation of Earth Science Technologies (InVEST-17) program.

HyTI is a low-cost compact long-wavelength infrared hyperspectral imager designed to monitor the evapotranspiration of the world's major crops (i.e., drop per crop). It is a 2U instrument on a 6U SmallSat and is the smallest LWIR hyperspectral instrument in its class. It was enabled by a low-cost, high-performance 640 × 512 pixel format FPA based on InAs/InAsSb SLS-BIRD technology.

HyTI was launched to the International Space Station (ISS) on March 21, 2024, and then launched from the ISS into space through the Nanoracks Small Satellite Launcher on April 18, 2024. It was the first spaceborne low-cost SmallSat LWIR hyperspectral instrument and is paving the way for SmallSat constellations for Earth observation.

NASA is also funding the development of a 1,280 × 1,024 pixel InAs/InAsSb SLS FPA with extended spectral coverage of up to 12 µm for HyTI-2, which is expected to launch in 2025 on a 16U SmallSat platform.

INSTRUMENTS THAT USE HOT-BIRDS DETECT HEAT ON EARTH FROM SPACE AND ON THE GROUND

Furthermore, the NASA Instrument Incubator Program (IIP-21) is supporting the development of a compact Fire Infrared Radiance Spectral Tracker (c-FIRST) instrument for wildfire detection, also based on the HOT-SLS-BIRD technology. c-FIRST is expected to launch in 2027. In the interim, MDL's HOT-BIRD technology has fueled innovations well beyond Earth observations from space.

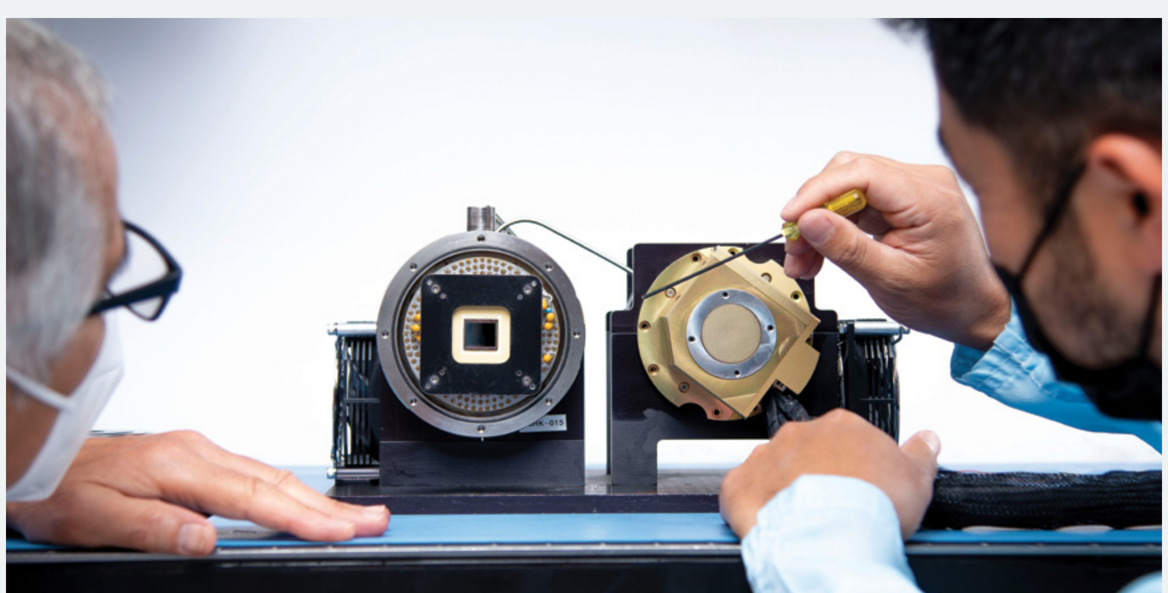
Major US defense contractors such as Raytheon and L3Harris have licenses to use HOT-BIRD for government applications.

The world's largest IR imaging camera company, Teledyne FLIR, has licensed 12 HOT-BIRD-related patents for commercial use and has produced a new generation of cameras using SLS-BIRD technology.

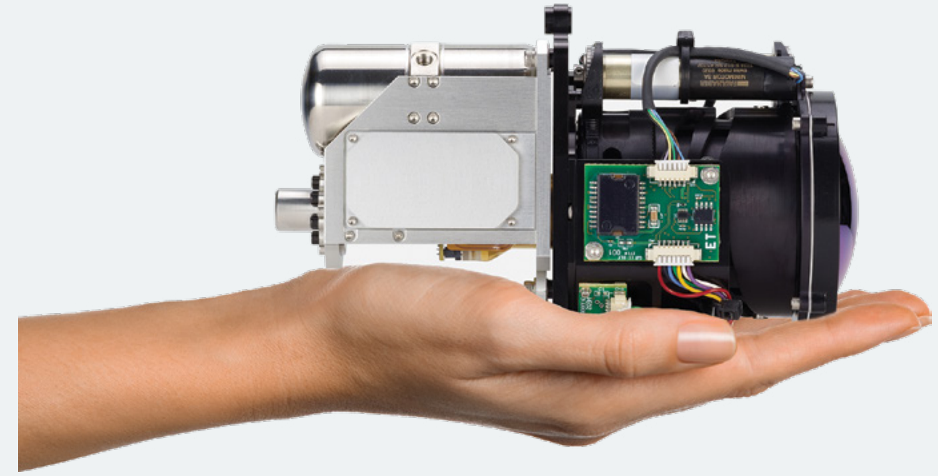
Teledyne FLIR has been selling these HOT-SLS-BIRD detector-based infrared imagers for a variety of purposes, such as building inspections, law enforcement, industry, public health, and search and rescue.

HOT-BIRD's advancements have been so crucial to IR sensing technology that its inventors received the 2018 Military Sensing Symposium (MSS) Herschel Award, which recognizes a major breakthrough in IR device science or technology, and the 2019 Levinstein Award, which recognizes lifetime achievement in the technical management of infrared detector technology.

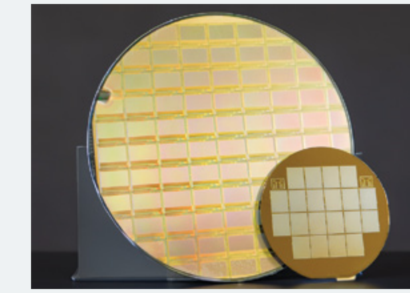
Installing a HOT-BIRD FPA in the dewer.



FLIR SENSING MORE



Neutrino® IS MWIR camera module and continuous zoom lens for SWaP applications.



Readout Integrated Circuit (ROIC) wafer and Detector wafer.

In 2011, MDL began working with Teledyne FLIR's OEM business unit as part of the US Army's Vital Infrared Sensor Technology Acceleration (VISTA) consortium with the goal of developing and bringing to market new infrared (IR) sensors using strained layer superlattice (SLS) detector materials.

SLS IR detector materials are typically made using advanced semiconductor growth techniques such as molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD). These detector materials promise significant advantages over traditional IR detector materials, such as mercury cadmium telluride (HgCdTe) and indium antimonide (InSb). For example, they provide wavelength tunability and multispectral operation and can function at higher operating temperatures, leading to improved system size, weight, and power (SWaP).

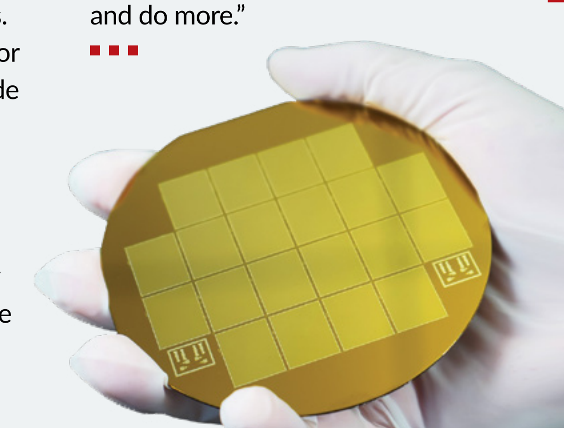
They have reduced dark current, performance improvements, and compatibility with large arrays. Additionally, they have longer lifetimes and longer-term stability than traditional IR detector materials. These improved IR sensors are crucial for military and dual-use applications such as surveillance, targeting, threat detection, and situational awareness in low-light or nighttime conditions.

In 2018, the technology proved promising enough that Teledyne FLIR entered into a licensing agreement with Caltech to use this MDL-developed intellectual property to manufacture IR focal plane arrays (FPAs) for their dual-use and military products. As the market-leading IR sensor merchant supplier to worldwide dual-use markets and a non-traditional defense contractor (NTDC) in US Department of Defense markets, Teledyne FLIR became the first industry partner to commercially license this MDL technology.

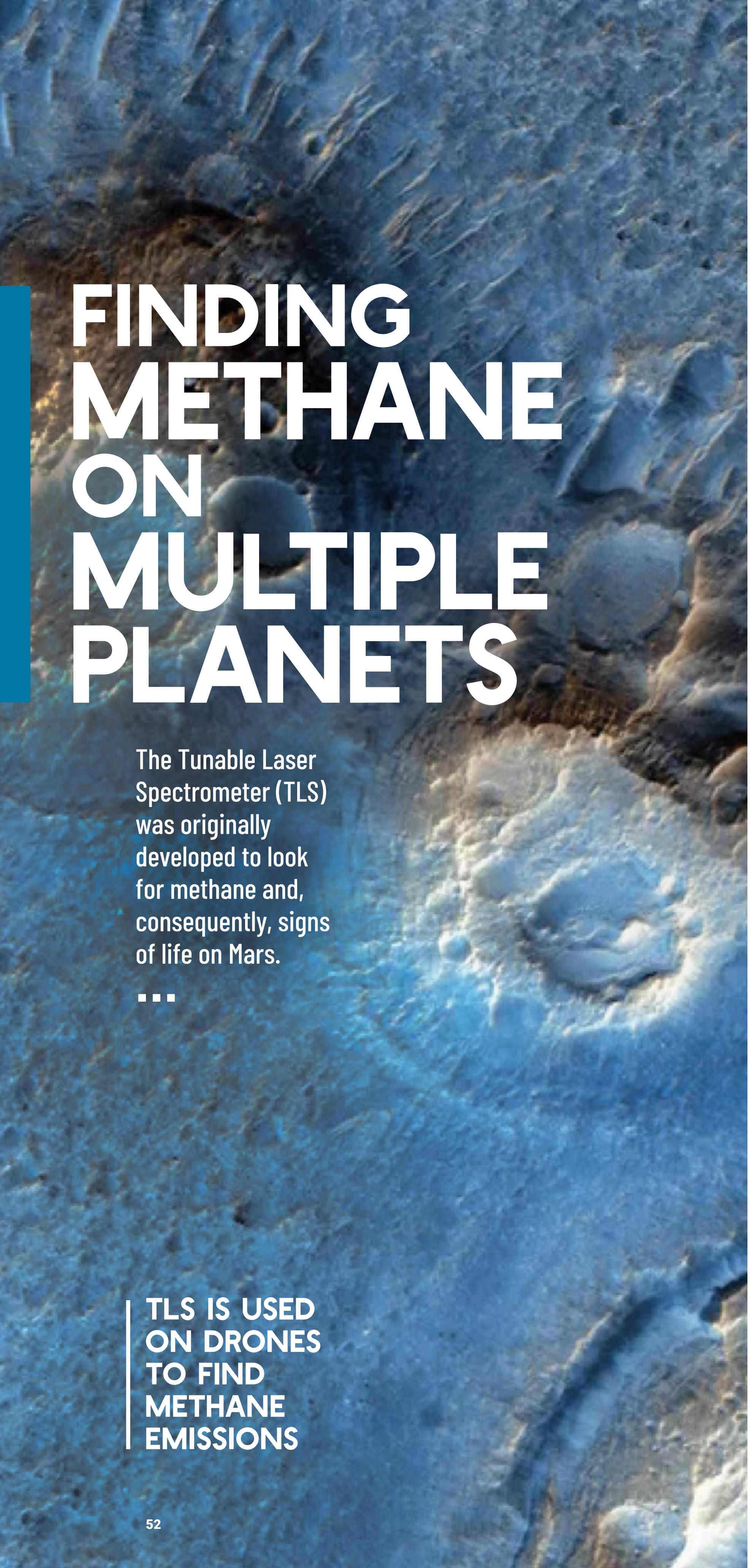
MDL TECHNOLOGY ENABLES A LINE OF TELEDYNE FLIR PRODUCTS

Today, Teledyne FLIR uses this newly acquired MDL technology to offer a wide portfolio of products under its Neutrino (www.flir.com/oem/neutrino-family/) portfolio and is changing the way the world is solving challenging problems.

According to Dan Walker, VP of product management at Teledyne FLIR, "The collaboration between Teledyne FLIR, the government, and industry partners, including JPL through the VISTA consortium, has resulted in a big leap forward for the US industrial base, our company's success, and ultimately for our customers. It has helped us fulfill our mission and purpose: to enable life-changing thermal sensing so the world can see and do more."



Detector wafer.



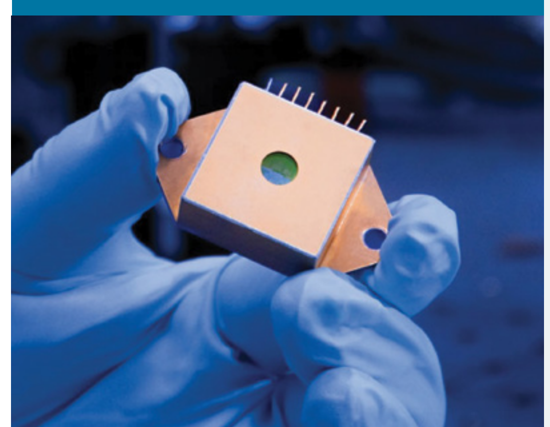
FINDING METHANE ON MULTIPLE PLANETS

The Tunable Laser Spectrometer (TLS) was originally developed to look for methane and, consequently, signs of life on Mars.

■■■

TLS IS USED ON DRONES TO FIND METHANE EMISSIONS

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



A low-power dissipation interband cascade (IC) laser fabricated at MDL inside a package designed specially for TLS. This device emits at 3.27 µm and was designed specifically to target absorption lines of methane.

Left: The image depicts a section of Acidalia Planitia, a flat plain in Mars' northern lowlands.

TLS was later miniaturized and repurposed to look for methane leaks on Earth at gas and oil wells, and it may one day be used to understand what happens as permafrost melts at the poles.

Methane is a potent greenhouse gas, and while much of the methane found on Earth is human generated, its largest source on this planet is actually bacterial activity. As a result, when Earth-based observers saw traces of methane on Mars, there was great interest in sending an instrument there on a rover to investigate further. Developed by JPL scientist Chris Webster and team, the TLS instrument represented a substantial advance because it had to be more powerful, sensitive, and accurate than previous space-ready spectrometers while also maintaining low size, weight, and power requirements.

This improved TLS — capable of detecting methane in the parts per trillion range — landed on Mars in 2012 aboard the Curiosity rover. For the last 12 years, it has periodically analyzed Martian air for traces of methane and other gases, such as carbon dioxide and water vapor. Since arriving on Mars, TLS has confirmed the presence of methane on the Red Planet, finding traces in multiple locations and larger plumes, as well.

MDL FABRICATED A LOW DISSIPATION IC LASER AND PLACED IT IN A SPECIALLY DESIGNED TLS PACKAGE

From the outset, though, it was thought that the TLS could also play an important role in the oil and natural gas industry, finding leaks and supporting companies in reporting any findings in this tightly regulated industry. To that end, JPL scientist Lance Christensen initiated multiple redesigns of the instrument. In 2013, he developed a handheld version of the instrument and worked with Andrew Aubrey from JPL's National Space Technology Applications Program Office and Pipeline Research Council International to test it. In another case, Christensen made the TLS light enough to fly on a drone and powerful enough to run 10 analyses per second. The tradeoff for these changes was a loss in sensitivity, down from the parts per trillion of the TLS on Mars to approximately 10 parts per billion. However, since gas leaks are generally detected around 50-100 parts per billion, the instrument was still more than capable of finding leaks.

By 2016, it was clear that there was commercial interest in the TLS and the technology that descended from it. In 2017, Aubrey and another JPL colleague licensed the sensor technology from JPL and used it to found SeekOps, a company that focuses on sensor manufacturing and emission detection services.

SeekOps manufactures its sensors in-house, which they then sell and use in their leak detection services. The sensors can be mounted on drones, which allows them to take aerial surveys in about a third of the time and with 1,000 times more sensitivity than a traditional system. SeekOps also offers a vehicle-mounted sensor that can allow gas companies to obtain data on potential leaks while conducting their usual day-to-day driving operations. In this way, SeekOps allows its customers to find active leaks, identify potential sites of future leaks, and prevent product loss.

As Earth warms, SeekOps' services may find another use: gathering data on areas where permafrost is melting. As the permafrost melts, the land will likely become swampy and begin to release methane into the atmosphere. SeekOps' drones may one day fly over these areas and help collect information on how methane emissions are changing there.

■■■

Methane leak detection with SeekOps drone-mounted sensor.

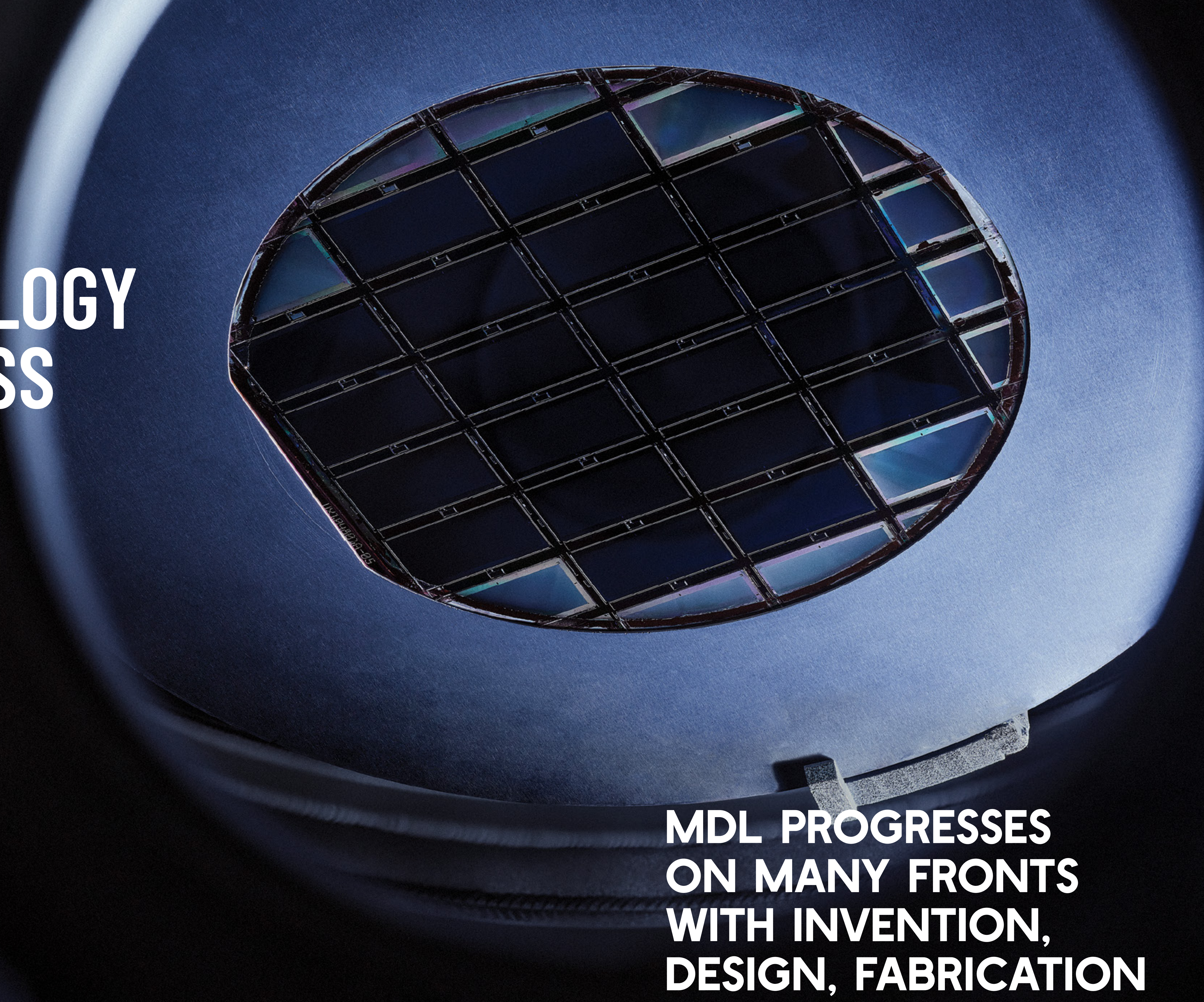
S.4

TECHNOLOGY PROGRESS

In the long term, the impact of MDL is evaluated by its ability to continuously incorporate novel or even disruptive technologies in space.

New and viable ideas must be identified and incorporated into the current state of the art. As many advances could come from non-space sectors, such sectors must be actively researched for potential ideas.

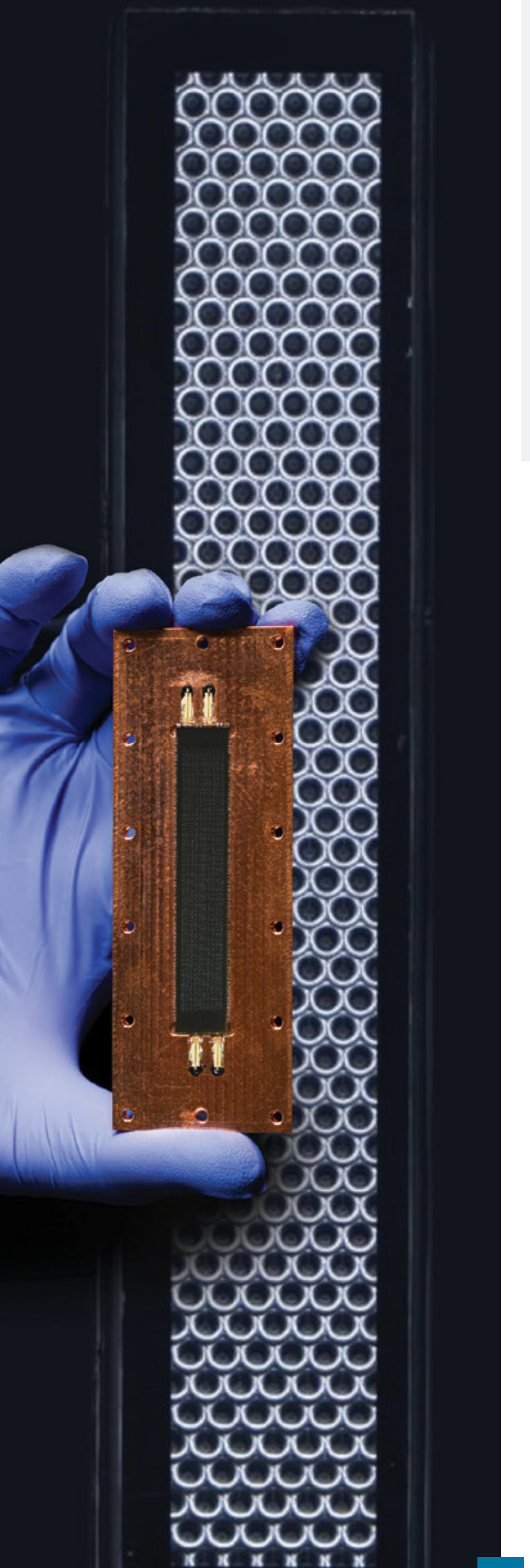
MDL FORGING AHEAD



MDL PROGRESSES ON MANY FRONTS WITH INVENTION, DESIGN, FABRICATION AND DELIVERY

FIRST LIGHT

MKIDs TECHNOLOGY



Left: A silicon microlens array fabricated using grayscale lithography.

PRIMA

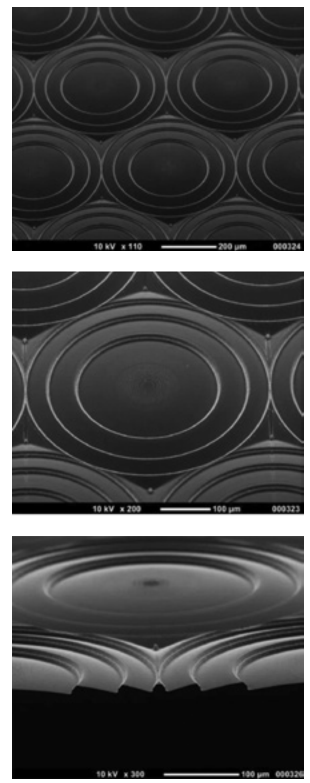
Three of NASA's key decadal questions seek to understand how galaxies and their supermassive black holes coevolve over time, to trace the astrochemical signatures of planetary formation, and to measure the buildup of heavy elements and interstellar dust over time.

A NEW SPACE OBSERVATORY WILL UNCOVER HOW GALAXIES AND BLACK HOLES COEVOLVE

The PRobe far-Infrared Mission for Astrophysics (PRIMA), a space observatory concept, will answer these questions by providing continuous spectral coverage from 24-261 µm to detect and measure the abundance of dust and heavy metals.

PRIMA will be enabled by an advanced technology: large arrays of superconducting detector arrays. It will use microwave kinetic inductance detectors (MKIDs) because they are simple to fabricate and can function at room temperature instead of cryogenic temperatures.

PRIMA will be the first far-infrared observatory in space, and it will cover much of the spectral gap between the James Webb Space Telescope and the Atacama Large Millimeter/submillimeter Array (ALMA).



Above: A close-up image of the Fresnel lenses, with a pixel pitch of 500 µm.

MDL will enable this project by fabricating the large-format superconducting MKIDs.

FMMI EYES ON IO

FACETED MIRROR MULTIBAND IMAGER

Jupiter's moon Io is known for its volcanic activity, and NASA's most recent Planetary and Astrobiology Decadal Survey proposes an Io Observer mission as a high priority. An MDL-developed faceted mirror multiband imager may be the key to high-resolution observations of this dynamic moon.

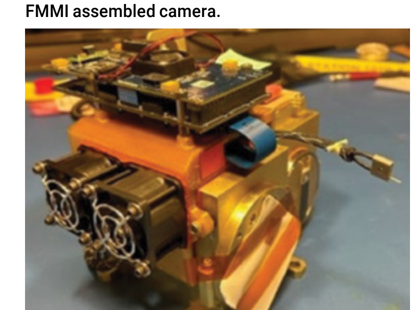
Io, the innermost moon of Jupiter, is a dynamic place known for its highly active volcanoes, which are thought to release lava as hot as 1,600 C. To better understand Io's volcanic eruptions, a new instrument capable of rapid, high-resolution imaging of targets at extreme temperatures must be developed. To that end, MDL scientists are developing a faceted mirror multiband imager (FMMI) that may eventually be sent to Io to uncover the most detailed data yet about this moon. Because the lava leaving Io is 1 million times hotter than the surrounding area, the FMMI must have a very large dynamic range of detection that can accurately register both the coldest and hottest temperatures on Io.

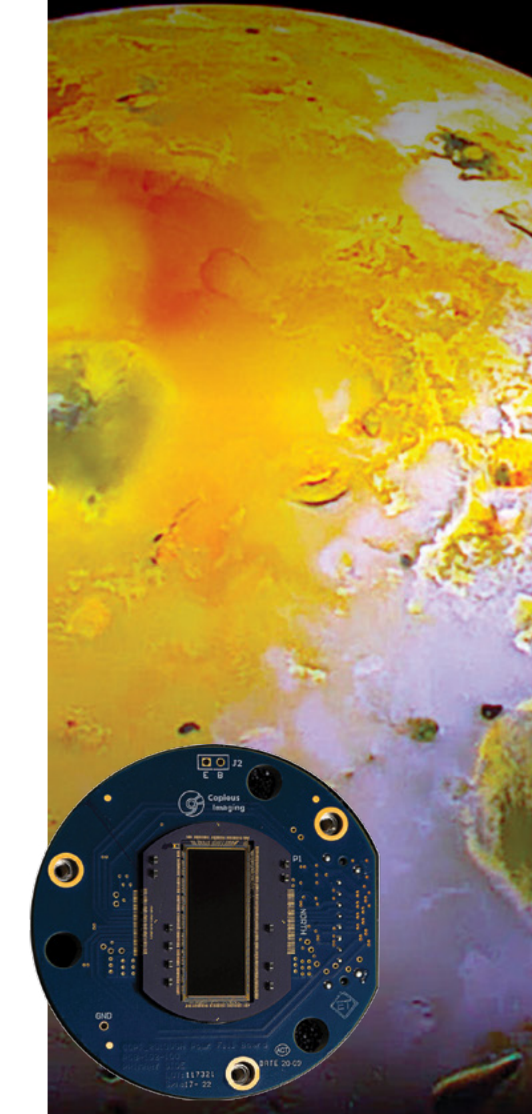
Additionally, because Io's volcanic activity is so unpredictable, and because the lava cools so fast once it erupts, the instrument needs to be able to capture images quickly — within 0.01 second — and ideally in as many wavelengths as possible.

The FMMI addresses these challenges via two novel enabling technologies: a digital focal plane array (DFPA) and an infrared imager with a faceted mirror. The DFPA combines high operating temperature-barrier infrared detector (HOT-BIRD) and digital-pixel readout integrated circuits (DROICs) to enable infrared imaging with a very high dynamic range at high operating temperatures and with good uniformity and stability. The faceted mirror consists of nine small mirrors that collect light reflected from a single concave mirror. The light reflects off each small mirror, allowing the measurement of the temperature at each point on Io. Essentially, the mirror captures nine distinct sets of images simultaneously.

The FMMI is part of NASA's Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program, which supports the development of hardware, instruments, systems, and components that can address the science goals of high-priority planetary missions but are still at a low technology readiness level (≤3). The FMMI may one day be included on a NASA Io Observer mission.

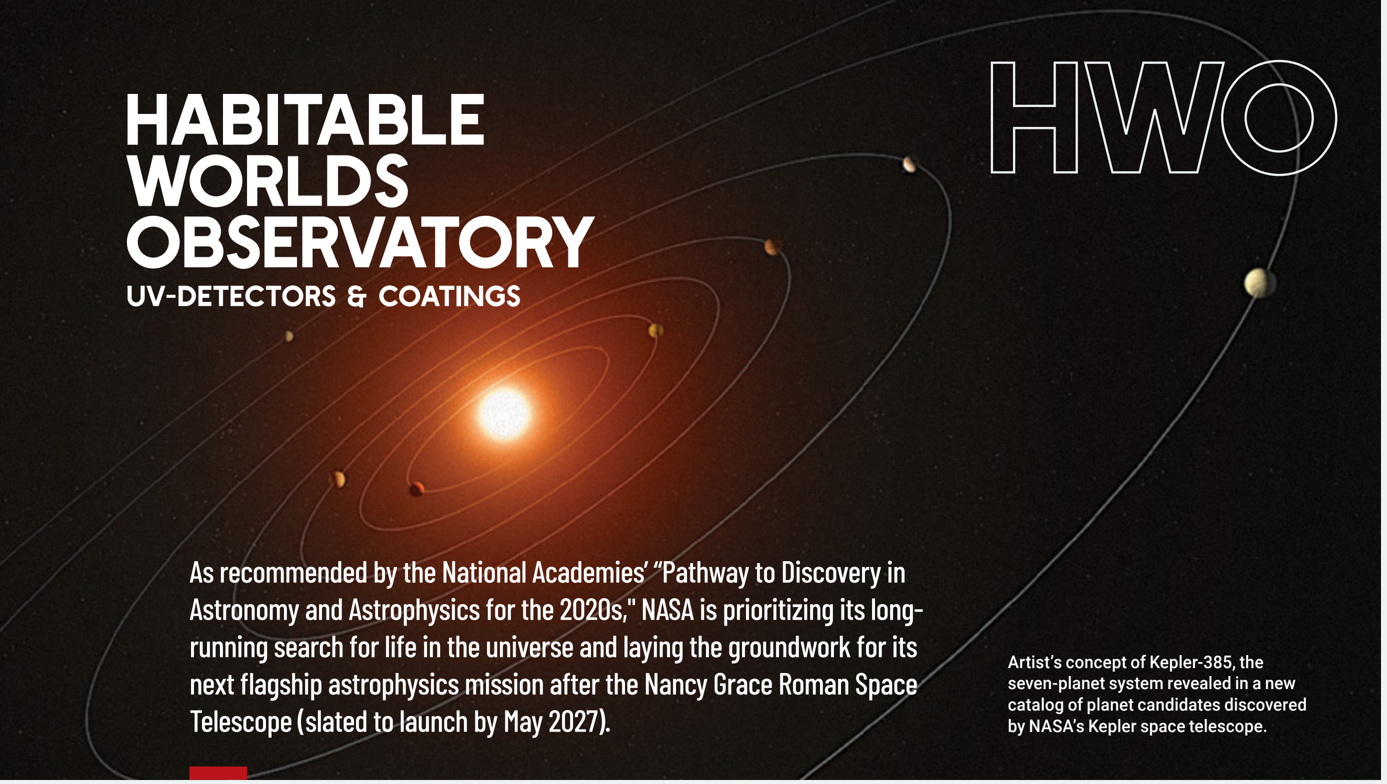
FMMI assembled camera.





A DFPA mounted on a daughterboard.

THE DATA WILL HELP UNDERSTAND MORE ABOUT IO AND ITS INTERIOR



HABITABLE WORLDS OBSERVATORY

UV-DETECTORS & COATINGS

HWO

As recommended by the National Academies' "Pathway to Discovery in Astronomy and Astrophysics for the 2020s," NASA is prioritizing its long-running search for life in the universe and laying the groundwork for its next flagship astrophysics mission after the Nancy Grace Roman Space Telescope (slated to launch by May 2027).

Artist's concept of Kepler-385, the seven-planet system revealed in a new catalog of planet candidates discovered by NASA's Kepler space telescope.

Currently referred to as the Habitable Worlds Observatory (HWO), this next flagship is a concept for a mission that would search for and characterize habitable planets beyond our solar system.

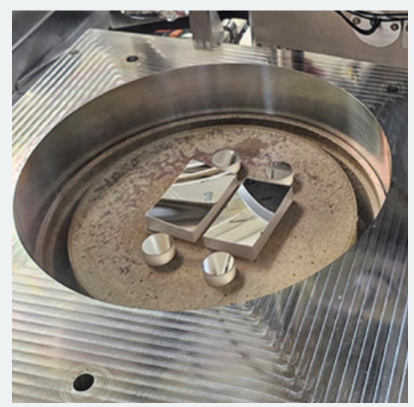
HWO would simultaneously provide powerful capabilities for transformational astrophysics discoveries, from our cosmic backyard of the solar system to the distant universe and everything in between. Building upon studies conducted for two earlier mission concepts — the Large Ultraviolet Optical Infrared Surveyor (LUVOIR) and Habitable Exoplanets Observatory — HWO would be designed specifically to identify and directly image at least 25 potentially habitable planets around other stars, closely examining their atmospheres to determine if life could possibly exist.

MDL IS ACTIVELY INVOLVED IN HWO CONCEPT MATURATION AND TECHNOLOGY DEVELOPMENT

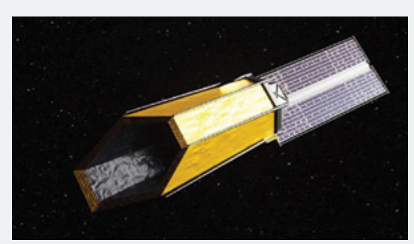
Several members of MDL's UV Detector Technologies Group are actively involved in the development of HWO, which is currently in the early stages of concept maturation.

MDL is also engaged in Technology Working Groups (TWGs) that seek to identify the critical technology elements for HWO, including those related to near-UV/visible detectors (Detector TWG) and far-UV detectors and coatings (UV TWG).

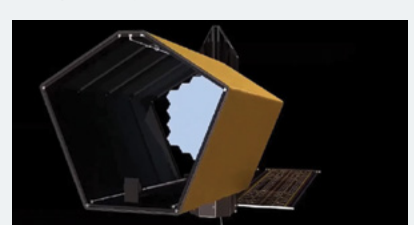
Maintaining an active role in these TWGs is critical to ensuring that MDL technologies are addressing the needs of future NASA missions and have a clear path to infusion.



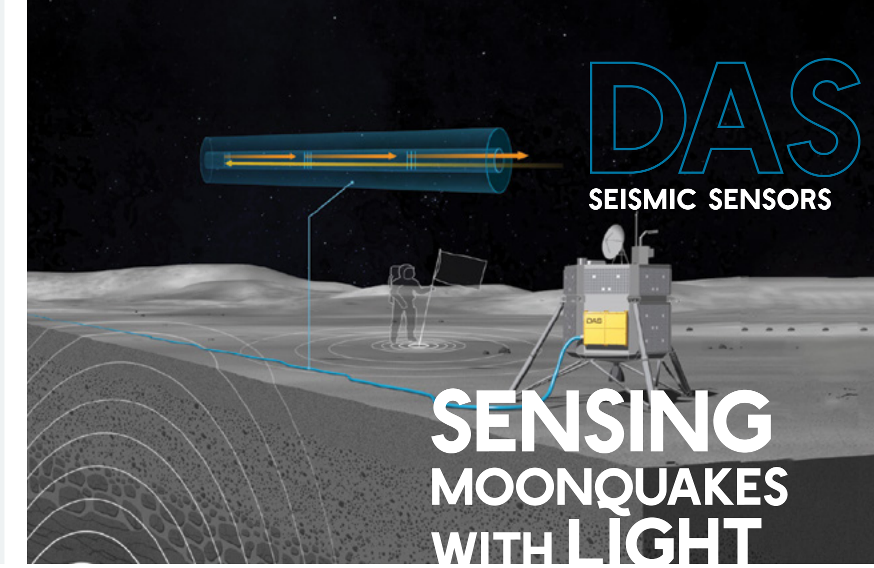
Flight-optic coating inside MDL ALD chamber for the Aspera Pioneers mission using a mirror coating that combines GSFC's eLiF process with thin ALD MgF_2 encapsulation.



This artist's concept features one of multiple initial possible design options for NASA's HWO. Credits: NASA's Goddard Space Flight Center Conceptual Image Lab.



An early design concept of NASA's HWO shows a large, segmented mirror surrounded by a protective shroud.



DAS

SEISMIC SENSORS

SENSING MOONQUAKES WITH LIGHT

By exploiting tiny imperfections in fiber-optic cables, the cables can be used to detect ground movement using a technique called distributed acoustic sensing (DAS). Future DAS arrays on the Moon will help sense moonquakes, understand lunar seismic activity, and better prepare for permanent settlements there.

Moonquakes can occur due to natural or artificial impacts, tidal forces caused by Earth's gravitational pull, or even thermal expansion/contraction due to the thermal fluctuations that occur during the lunar day/night cycle. Much like on Earth, studying the seismic activity on the Moon can reveal new insights into its internal structure and history.

Seismology and geophysics on Earth are undergoing a revolution, propelled by developments in optical fiber DAS techniques. These methods convert an existing fiber-optic cable into a dense array of ground deformation sensors, spaced every few meters, by periodically launching pulses of light into the optical fiber cable at one end and measuring the small "echoes" of light that return.

DAS takes advantage of the small density fluctuations present along the optical fiber that are "frozen in" during its fabrication. These defects exist at fixed positions in the fiber and reflect a tiny amount of the light back toward the source. Therefore, consecutively launching pulses of light into the fiber allows the observation and monitoring of changes to the relative positions of these imperfections, thereby determining where and by how much the fiber is being stretched or compressed relative to a previous measurement. The dense array-like nature of DAS measurements is particularly suited for the Moon due to the high scattering and low attenuation of its crust, which "smears" seismic signals over short distances. This scattering and low attenuation, combined with low numbers of deployed sensors, such as in the case of the previous Apollo missions, leads to challenges when picking and detecting seismic phases. In addition, DAS holds an advantage over other sensing array alternatives by keeping all of its active elements contained in a single interrogator that can be housed in a lander, while the sensor array itself consists of a single passive element (a single optical fiber).

Commercial DAS systems, however, are generally not suitable for deployment in space or to the Moon due to their mass and power requirements. These systems are usually designed for reconfigurability and compatibility with existing telecommunications fiber optics.

At MDL, and in collaboration with Caltech, engineers are working to miniaturize and tailor the performance metrics of DAS for the lunar environment by changing the interrogator and combining it with specially designed optical fibers. The goal is to develop an instrument that can detect and localize moonquakes, improve our understanding of the Moon's tectonic activity and seismicity levels, and enable new studies of the impact history of the lunar crust.

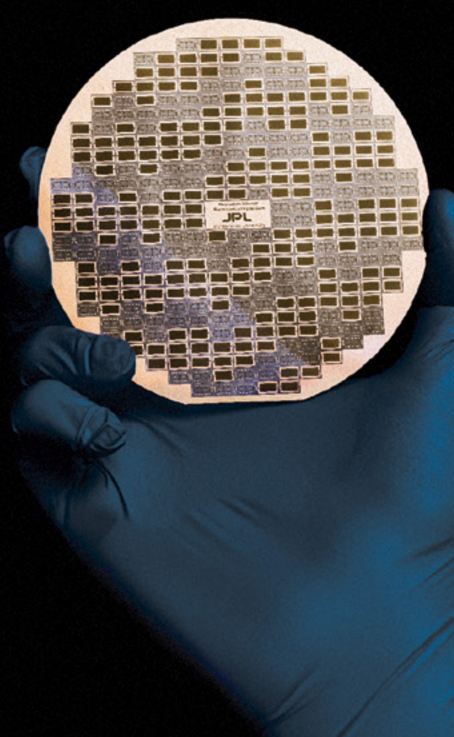
This new understanding of lunar seismicity will improve the ability to safely plan and maintain permanent structures on the Moon, such as lunar bases.

Top: An artist representation of the Lunar DAS concept, which uses a fiber-optic cable as a dense array of seismic sensors by analyzing laser backscatter.

BUILDING A SEISMIC NETWORK ON THE MOON USING OPTICAL FIBERS

A HOT TAKE ON SUPER-CONDUCTING

MDL researchers have achieved the production of wafer-scale magnesium diboride (MgB_2), thin films for superconucting device applications such as thermal kinetic inductance detectors and superconducting nanowire single-photon detectors. MgB_2 will one day enable exquisitely sensitive detectors that have lower cooling requirements than ever before.



Coplanar waveguide microwave resonators and other test chips patterned in MgB_2 film deposited on 100 mm sapphire substrate.

Most superconducting materials only behave as such near 4 K, a temperature that is difficult and expensive to achieve, so research has aimed to identify materials that superconduct at higher temperatures.

In 2001, MgB_2 was shown to behave as a superconductor at higher temperatures (39 K). Since MgB_2 is a metallic superconducting material with the potential to enable space science missions over a wide array of remote sensing applications, research on MgB_2 films at MDL began in 2017. The first in-house superconducting films at MDL were demonstrated in 2018. Since then, MDL has developed the first scalable process to deposit uniform thin films of MgB_2 to reliably reproduce and fabricate the detectors and electronics critical to future NASA science instruments.

MDL teams have developed MgB_2 thin films with a critical temperature as high as 37 K. Since a space cryocooler operating at 4 K requires 100-fold more power than one operating at 20 K, with attendant significant instrument costs, this advance has important implications. Therefore, using MgB_2 thin films that function at 10-20 K or more could enable new instrument innovations, including state-of-the-art sensitivity at elevated operating temperatures in remote sensing instruments, such as THz mixers and direct detection bolometers in the mid- and far-infrared range, at much lower cost.

Additionally, above the superconducting gap, there is significant loss in signal transmission, so the extreme nonlinearity prevalent in most superconductors means that most cannot be used at higher frequencies. However, the large superconducting gap in MgB_2 could enable technologies into terahertz frequencies while minimizing signal loss.

Since the first demonstrations of MgB_2 thin film fabrication, ongoing work has focused on improving MDL's fabrication capability. Uniform films with less than 0.5 nm root mean square (rms) roughness over a 4-inch wafer have been fabricated, and fabrication techniques have been developed for real-world applications.

The first outputs of this process were microwave resonators, which demonstrated large active-area fabrication and low radio frequency (RF) loss in the material.

MDL HAS DEVELOPED A METHOD TO MAKE WAFER-SCALE THIN FILMS OUT OF MgB_2

The next step has been to demonstrate practical devices with these films, including kinetic inductance bolometers, single-photon detectors for optical communications in space, and terahertz mixers for high-resolution spectroscopy. MDL researchers are also developing a family of devices utilizing nonlinear kinetic inductance toward terahertz frequencies. These devices include frequency multipliers, parametric amplifiers, and active phase delay lines. They will also enable mm/sub-mm spectroscopy with unprecedented sensitivity and a resolution ranging over 5 orders of magnitude, facilitating the study of star-forming regions and galactic evolution.

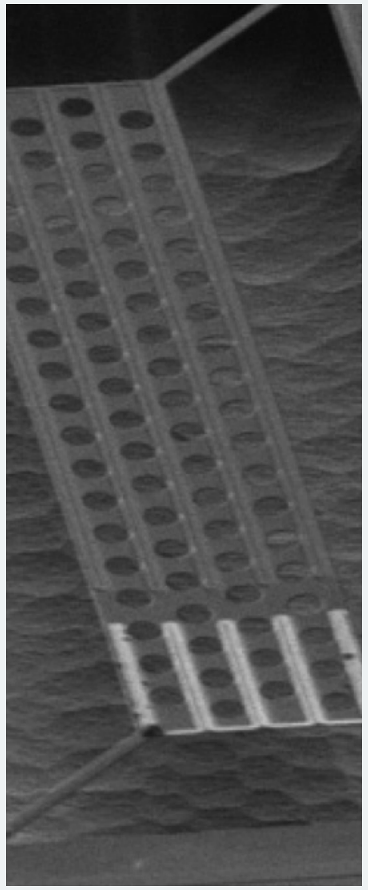
Perhaps the most impactful part of MDL's work on MgB_2 films is that their depositions use common physical vapor deposition (PVD) techniques, which will enable the wide adoption of this unique material. The advancements in fabrication techniques of these films by MDL personnel have been significant and steady, with two proof of concept devices, thermal kinetic inductance detectors (TKIDs) and superconducting nanowire single-photon detectors (SNSPDs), recently demonstrated.

A TKID made with MgB_2 offers an easy-to-read-out kilopixel array format for detectors that can achieve or improve on state-of-the-art sensitivities. The high critical temperature of the thin films offers a new temperature range for these bolometers. At 4 K, they can achieve background-limited noise performance for applications like detection through fog and weather. At 25 K, they can be integrated into an instrument with a small-format cryocooler to fit within a planetary instrument budget and offer unprecedented sensitivities for planetary science themes, particularly important for ice giant surveys and outer solar system targets, where background noise can be significantly lower than 300 K terrestrial targets. MDL's expertise in developing similar technologies has been leveraged to quickly marry the novel detector scheme with the new material, advancing the technology readiness level of the technology much faster than historical averages.

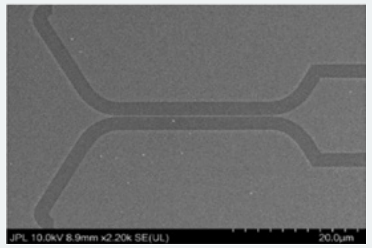
SNSPDs are devices that can count incident photons on a receiver system with efficiencies near unity, low dark count rates, and ultra-fast (picosecond) reset times that can operate from the UV through the mid-IR. SNSPDs made with MgB_2 have the potential to stretch the operating temperature to well above 4 K and potentially as high as 20 K so that the same small-format cryocoolers used for MgB_2 TKIDs can also carry SNSPDs to space for both space science instruments and optical communication systems. An MDL team is the global leader in SNSPDs, and they have integrated with the MgB_2 team to demonstrate the first photosensitive SNSPDs made with in-house MgB_2 thin films.

MgB_2

NEW SUPERCONDUCTING DEVICES PROMISE TO REVOLUTIONIZE ASTRONOMY



SEM image of a released bolometer. The bright lines on the bottom are a gold trace that is used as an embedded heater.



SEM of nanowires fabricated from MgB_2 films at MDL.

S.5 DIVERSITY

SHAPING THE INNOVATORS OF THE FUTURE

Dr. Bouschet received his PhD from the University of Montpelier in France and started at MDL in June 2023.

Maxime has extensively studied the performance and transport properties of long-wave and very-long-wave (up to 15 µm) superlattice infrared photodetectors, with the goal of improving photodetector performance. He works with the Infrared Team on photodetector processes, material characterization (photoluminescence and lifetime), and electrical and electro-optical characterization (dark current, spectral response, and quantum efficiency). He is currently working on fabricating the first multi-spectral sensor coupling plasmonic filter and infrared photodetector (CBIRD) that covers the 1.8-2.6 µm band. Its successful fabrication will allow the identification of a wide range of minerals relevant to Martian geology and astrobiology.

Maxime proposed a superlattice-based avalanche photodiode (APD) covering the full mid-wave range and built a high-voltage setup for its electrical characterization.

MAXIME BOUSCHET

LUIS COSTA

Dr. Costa received his PhD in electrical engineering from the University of Alcala, Spain, specializing in photonics. His background and interests span optical fiber sensing, nonlinear optics, and integrated photonics.

At MDL, he focuses on developing integrated photonic processors for coronagraph applications and developing distributed acoustic sensors for planetary applications.

His current research focuses on developing integrated photonic coronagraphs as an alternative to the conventional free-space optic setups. Integrated photonic coronagraphs leverage the ability to perform linear computing operations on the electric field of light, before detection, inside a photonic integrated circuit, which would allow the separation of starlight from exoplanet light. He is also working on developing seismic sensor arrays for planetary applications using optical-fiber distributed acoustic sensing. These methods convert a single deployed fiber optic cable into hundreds of seismic sensors spaced every few meters, all of them interrogated from a single instrument that can be placed on a lander or rover. This strategy is particularly relevant for lunar applications, where having a dense network of sensors can overcome several challenges that single sensors face in highly scattering mediums, such as the Moon's crust.

Dr. Faramarzi received his PhD in physics from Arizona State University, where he worked on superconducting devices and detectors. He joined MDL as a NASA Postdoctoral Fellow in February 2023.

His research is focused on developing quantum-linked parametric amplifiers using superconducting materials with nonlinear kinetic inductance. During his first year at MDL, he helped demonstrate a 4-8 GHz near-quantum-limited traveling wave parametric amplifier (TWPA). The device has a wide bandwidth and a high dynamic range, making it superior to Josephson TWPAs. He also demonstrated the first sub-GHz quantum TWPA.

Farzad's work incorporates two groundbreaking innovations: the use of a titanium nitride (TiN) microstrip line, which helps significantly reduce the pump power requirement, and the operation of a KI-TWPA as both an amplifier and as a frequency upconverter. The TWPA covers the sub-GHz range with near-quantum-limited noise performance and signal gain frequency tunability in the 450-800 MHz range. These amplifiers can be used to read out microwave kinetic inductance detectors (MKIDs) such as the one developed for the PRobe far-Infrared Mission for Astrophysics (PRIMA).

FARZAD FARAMARZI

JOHN FEMI-OYETORO

Dr. Femi-Oyetoro received his PhD in physics from the University of North Texas and joined the MDL NEXT postdoctoral program in 2021.

His research initiatives include advancing the growth of high-quality superconducting transition metal nitrides, such as titanium nitride (TiN), using plasma-enhanced atomic layer deposition (PEALD). These materials are crucial in astronomy, particularly in cosmic microwave background (CMB) studies, facilitating photon detection, quantum amplification, and 3D integration with superconducting through-silicon vias (TSVs). Superconducting film-coated TSVs in transition edge sensors with superconducting quantum interference device (SQUID) multiplexer (MUX) readout enable background-limited sensing in the submillimeter and far-infrared spectrum, as demonstrated by the Primordial Inflation Polarization Explorer (PIPER). The films exhibit precise uniformity, homogeneity, and seamless 3D integration, with critical temperatures comparable to those of conventional sputtering methods, maintaining superconductivity even in 3D trenches with an aspect ratio of up to 40.

John is currently optimizing the films for kinetic inductance parametric amplifiers (KIPAs), with the technology in provisional application for a U.S. utility patent and the results under review in a high-impact journal.

Dr. Gamage received her PhD in analytical chemistry from the University of Kansas, where she developed microfluidic devices, nanopores, and workflows to extract cancer and virus biomarkers from body fluid specimens.

Sachindra is a NASA Postdoctoral Program fellow working in the Chemical Analysis and Life Detection Group at MDL, where she focuses on developing analytical strategies to improve the detection sensitivity of low-abundant chemical biosignatures in complex sample matrices.

To this end, she is optimizing protocols to extract and detect key organic molecules such as amino acids and fatty acids from Atacama Desert soil samples, which serve as a Martian regolith analog, using subcritical water extraction and capillary electrophoresis coupled to various detection methods. These target molecules are also characterized for astrobiologically pertinent chemical patterns such as chirality, chain length, and relative abundance, which can serve as potential molecular biosignatures indicative of life beyond Earth.

Additionally, she is developing a fully automated front-end microfluidic system that can preconcentrate soluble organic and inorganic compounds to enhance the detection sensitivities of integrated chemical analyzers. This system will comprise inline electrochemical sensing elements to understand bulk sample properties before downstream analysis and to provide the context of the environment where the samples are investigated.

SACHINDRA GAMAGE

ANDREAS GOTTSCHOLL

Dr. Gottscholl received his PhD from the Julius-Maximilian University of Wuerzburg in Germany, where he focused on hexagonal boron nitride (hBN) and identified the first optically addressable spin defect in this graphene-like 2D material.

At MDL, Andreas is developing a new generation of quantum magnetometers using spin defects in solid-state systems such as diamond, silicon carbide (SiC), and hBN. He employs various readout techniques to access the spins, with a primary focus on optically detected magnetic resonance (ODMR). ODMR uses the brightness of a sample to differentiate between spin states.

In addition to ODMR, Andreas is working on a novel RF-based readout of the spin system using the system as a maser. The objective is to create a SiC maser that operates at room temperature and functions as a clock with a frequency output proportional to the magnetic field. Having previously developed the first SiC maser in his hometown, Andreas aims to update the design to enable vector magnetometry.

Dr. Harrysson Rodrigues is a former Swedish National Footvolley Champion and received her PhD from Chalmers University of Technology in Sweden. She specializes in fabricating and developing state-of-the-art microdevices, such as electrical components for sensing and detection.

Unlike Earth, with its protective atmosphere, the environment in much of the solar system is too harsh for everyday electronics to survive. To address this problem, Isabel's current research focuses on robust III-V material-based microdevices for the extreme environments found in space.

Isabel's research focuses on developing an infrared (IR) sensor instrument for imaging in harsh environments. The sensor head is based on an IR resonator sparse array design, crafted to ensure minimal loss in overall imaging resolution while routing signals from each pixel (resonator) to integrated electronics, engineered to withstand and operate effectively at temperatures up to 470 C (the surface temperature on Venus). She recently obtained new data where measurements were conducted using a sparse array device illuminated by an IR source. These measurements captured the array's resonant response at various temperatures, resulting in a linear temperature dependence and a detectable frequency shift at 490 C with and without IR illumination. She is now focusing on the readout circuit and system, where monolithic integration of high-electron-mobility transistors (HEMTs) are key components of low noise amplifiers (LNAs) for the sensor signals in a larger-scale application specific integrated circuit (ASIC). The goal is to operate the instrument on the surface of Venus or other unforgiving harsh space environments.

ISABEL HARRYSSON RODRIGUES

EMANUEL KNEHR

Dr. Knehr earned his PhD from the Karlsruhe Institute of Technology in Germany, focusing on uniform superconducting thin films, frequency-domain multiplexing, and innovative optical coupling for arrays of superconducting nanowire single-photon detectors (SNSPDs).

At MDL, Emanuel is working on large-format single-photon cameras based on thermally coupled superconducting nanowires. This technology is being co-developed at the National Institute of Standards and Technology (NIST) and JPL and targets low-photon-flux imaging applications. Emanuel is currently improving the resolution, spectral range, and timing performance of these arrays with the goal of meeting the requirements for a science camera for the proposed Habitable Worlds Observatory.

To date, a high fill factor prototype with 230,000 pixels has been developed at JPL. He is also collaborating with a group at Caltech to read out neutral atom qubit arrays, where the exceptional efficiency and timing performance of his sensors could considerably reduce the collection time when reading out quantum states. This enhanced efficiency and performance could enable scalable, fault-tolerant neutral atom systems.

Apart from thermally coupled arrays, he is working on large-format microwire arrays that are used at Caltech for scintillation experiments to search for dark matter and at Fermilab for beamline tests.

HANI NEJADRIAHI

Dr. Nejadriahi earned her PhD in photonics from UCSD, focusing on integrated technologies for space exploration. She specializes in designing, fabricating, and optimizing photonic components, including laser optics for quantum sensors, semiconductor lasers, and mid-to-long infrared devices.

Hani has made significant contributions to MDL's initiatives in laser optics and the miniaturization of cold atom sensors. She developed an ultra-low-loss silicon nitride (Si_3N_4) platform in the 780-852 nm wavelength range, enabling the creation of an ultra-narrow-linewidth (65 Hz) external cavity laser at 852 nm. This platform can also be adapted to shorter wavelengths where commercial lasers fall short.

Additionally, she has been instrumental in developing a novel gallium nitride (GaN)-on-sapphire platform for integrated photonic acousto-optic modulators (AOMs) to advance quantum sensors, particularly gravity gradiometers. This platform achieves low optical losses, and she and her colleagues are collaborating with Yale University to explore strategies to enhance AOM efficiency and minimize power usage. Hani is a key e-beam team member, designing and fabricating diffractive optical elements for critical missions such as the Carbon Balance Observatory (CARBO), the Combustion Product Monitor (CPM), and the Telescope for Orbit Locus Interferometric Monitoring of our Astronomical Neighbourhood (TOLIMAN).

Dr. Shanks received his PhD in physics from the University of Arizona and joined MDL in August 2022. His postdoctoral work focuses on advanced lithography techniques, such as grayscale e-beam lithography of diffractive optics and atomic layer etching of superconducting nanowire single photon detectors (SNSPDs).

This work includes the fabrication of phase masks for the Habitable Worlds Observatory, which is designed to directly image Earth-like exoplanets using a coronagraph. One such phase mask imparts the phase steps representative of the segmentation of the primary mirror of the telescope by depositing layers of titanium that are only a few atoms thick in a hexagonal pattern, like that of the James Webb Space Telescope.

Additionally, in his work on SNSPDs, Daniel has developed a novel nanowire fabrication technique that uses atomic layer etching to both thin and smooth nanowire masks, allowing longer wavelength photon detection at a given temperature.

This advanced lithography technique is important because SNSPD performance is closely linked to the width and line edge roughness of the superconducting nanowire. His innovation will be crucial in the development of SNSPD cameras that can detect visible light at 4 K.

DANIEL SHANKS

LENA VINCENT

Dr. Vincent received her PhD from the University of Wisconsin-Madison, where she researched the chemical origins of life on Earth.

Now, as part of the Chemical Analysis and Life Detection and Planetary Science Laboratory Studies groups at JPL/MDL, she is working on experimentally simulating the surface conditions on ocean worlds to assess biosignature preservation there.

Ocean worlds such as Europa and Enceladus are thought to be some of the best candidate environments for finding life beyond Earth, so there is great interest in looking for signs of life, or biosignatures, on these worlds on future astrobiology missions. However, it is unclear if such biosignatures would persist long enough to be detected at their surfaces given that the extremely harsh temperature, vacuum, and radiation conditions on these ocean worlds destroy the chemistry of life as we know it.

Lena's research is focused on experimentally assessing the preservation potential and detection of biosignatures recovered from microbes by exposing them to simulated ocean world surface environments. This simulation involves placing hardy microbes into relevant conditions using a cryogenic vacuum chamber and analyzing the resulting biosignatures using several techniques. This work may provide important guidance for future attempts to detect signs of life beyond Earth.

Dr. Yasar received his PhD in materials science from the University of Wisconsin-Madison in 2020.

At MDL, he focuses on X-ray imaging detectors, far-infrared (IR) bandpass filters, quantum sensor gravity gradiometers, micro-optics packaging, and optical microelectromechanical system (MEMS) reliability. Firat has developed and advanced a provisionally patented X-ray imaging detector using wide bandgap materials and photonic crystals, achieving <1 µm spatial, ~3 ns temporal, and 3% spectral resolutions at 662 keV. His work on gallium nitride (GaN) photonic crystals led to a publication in the "Journal of Vacuum Science and Technology" ("JVST") and a collaboration with the Nara Institution of Science and Technology, with further research under review. He fabricated far-IR filters for superconducting nanowire single photon detectors (SNSPDs), covering ranges from 20-120 µm, supporting the PRobe far-Infrared Mission for Astrophysics (PRIMA) mission's study of galaxy and solar system formation. He is preparing a new technology report and a journal manuscript on this work.

Additionally, Firat built a laser optic system for atomic cooling using cesium atoms for a gravity gradiometer, incorporating lasers, variable optical attenuators (VOAs), microelectromechanical system (MEMS) switches, and polarization-maintaining (PM) fibers, successfully cooling tens of millions of atoms to below microkelvin temperatures.

FIRAT YASAR

FUTURE-PROOFED PATTERNING

LITHOGRAPHY SYSTEMS

MDL's wafer patterning capabilities have kept it at the forefront of the microdevice field, but aging equipment has required a new machine. Historically, MDL has invested in wafer patterning capabilities that have balanced resolution with throughput.

This strategy was aligned with MDL's focus on proof-of-concept demonstrations and NASA programs needing exceptionally high-performance microdevices with small to moderate numbers of delivered parts. In addition, it was necessary to accommodate multiple wafer-size diameters to enable both Si and GaAs processing.

Thus, MDL could make effective investments in somewhat dated but cheaper stepper technologies (e.g., 180 nm node and earlier) while allowing higher resolution needs (e.g., 90 nm node and smaller/later) to be filled with its JEOL e-beam lithography system.

INVESTMENT

MDL's patterning technology has been instrumental in supporting high-performance applications, but two significant challenges have emerged. First, MDL's equipment is aging and becoming obsolete: its existing patterning systems, the Canon FPA3000 EX3 and EX6 steppers, are reaching their end of life. The availability of replacement parts, especially electronic boards and computer controllers is becoming increasingly problematic.

Furthermore, these systems rely on unique excimer lasers, which are now rare and have minimal support, adding to the difficulty of system maintenance. As these systems age, the risk of downtime and operational disruptions increases, necessitating either extensive maintenance efforts that can require reengineering obsolete systems or investments in new technology.

Second, demand for high-resolution and large-scale patterning is increasing. The growing need for devices with higher resolution and larger arrays — particularly for metasurfaces used for the wavefront correction of large mirror telescopes, single photon detectors for deep space optical communication, and microwave kinetic inductance detectors (MKIDs) for cosmic microwave background (CMB) research — has outstripped MDL's current capabilities. While the existing JEOL JBX9500FS e-beam lithography system offers exceptional resolution with a 3.6 nm spot size, its write times are lengthy, making it impractical for moderate to large production runs.

Addressing these challenges are crucial for MDL to continue meeting the demands of cutting-edge applications and maintaining its competitive edge in the patterning technology field. Consequently, MDL has invested in an ASML PAS 5500-1150C ArF Lithography System (with 90 nm resolution to 65 nm with off-axis illumination). The PAS 5500-1150C offers the important capability of wafer-scale processing at these fine resolutions, so entire wafers, rather than individual chips, can be patterned in a single operation. The ability to process 65-90 nm features at wafer-scale allows for the simultaneous production of multiple devices, thereby increasing throughput and reducing fabrication times. More importantly, wafer-scale processing enhances yield, as it minimizes the variability and defects associated with smaller-scale operations.

This investment will address both of MDL's major wafer patterning challenges. It will allow a smooth transition from the older systems, which are reaching their end of life, and provide the enhanced resolution required for future needs, all in a platform with a manufacturer commitment for long-term customer support.

From a programmatic standpoint, this ASML stepper has capabilities that will also yield immediate benefits. For example, it will benefit detectors for the Deep Space Optical Communications Lunar Laser Communications Demonstrator and the Performance-Enhanced Array for Counting Optical Quanta (PEACOQ) detector. It will also help all work associated with the MKID and transition-edge kinetic induction detector (TKID) fabrications needed for current CMB polarimetry deliverables for balloon experiments and the Keck Telescope, as well as those for the proposed Precision Radiometry and Imaging for Millimeter Astronomy (PRIMA) mission.

MDL'S NEW ASML SCANNER WILL BE A TRANSFORMATIVE CAPABILITY FOR JPL AND NASA WHEN IT COMES ONLINE IN EARLY 2026

ASML PAS 5500 lithography system.
Credit: ASML.

IN MEMORIAM PAULMAKER

Dr. Maker, who spearheaded MDL's efforts in electron beam (e-beam) lithography, passed away on April 24, 2024, at the age of 89. He is survived by his wife, Carol; his children, Brad and Alison; his six grandchildren; and his four great-grandchildren.

Paul Maker attended the University of Michigan, earning a bachelor's degree in engineering and a PhD in physics. In 1961, he joined the Ford Motor Company Scientific Labs, where he conducted pioneering work with lasers in the field of nonlinear optics. Notably, his laser was shown on the July 1963 cover of "Scientific American", and "Maker fringes" are named after his technique for measuring second-harmonic generation in crystals.

Paul worked at Ford until taking a special early retirement in 1987 at the age of 53, having been recruited by the "Ford Mafia" team at JPL to start MDL. He led MDL's effort in e-beam lithography, and until he retired in 2002, he utilized the e-beam's unmatched precision to develop novel fabrication processes that are still in use today. Paul invented direct-write e-beam techniques for creating grayscale surface-relief patterns, enabling the fabrication of high-efficiency diffractive optics, including blazed gratings, lenses, and computer-generated holograms.

More importantly, he invented e-beam methods for fabricating such grayscale diffractive optics on convex and concave substrates, pushing the e-beam tool far beyond its design intent of writing on flat wafers. The ability to fabricate curved diffraction gratings enabled JPL to develop novel types of imaging spectrometers that have flown on aircraft and spacecraft to map the composition of Earth, the Moon, Mars, and soon, Europa.

Dr. Maker was awarded the NASA Exceptional Service Medal in 1996 and the NASA Exceptional Achievement Medal in 2002, but his legacy of contributions to MDL will endure. The pillars of Paul Maker's life were his love of family, learning, and friends. At his core, he was a genuine scientist with an unending curiosity about our world and the universe.

PAUL UTILIZED THE E-BEAM'S UNMATCHED PRECISION TO DEVELOP NOVEL FABRICATION PROCESSES THAT ARE STILL IN USE TODAY

HE SINCERELY CARED ABOUT PEOPLE AND GENUINELY WANTED THEM TO BE HAPPY

APPENDIX

Peer-Reviewed Journal Publications

1. Ballew, C., Roberts, G., Faraon, A., "Multi-dimensional wavefront sensing using volumetric meta-optics." Accepted at Optics Express. Pre-print: https://arxiv.org/abs/2301.10346.
2. Costa, L., Varughese, S., Mertz, P. et al. Localization of seismic waves with submarine fiber optics using polarization-only measurements. Commun Eng 2, 86 (2023). https://doi.org/10.1038/s44172-023-00138-4
3. Curwen, C. A., et al. "Phase Locking of a THz QC-VECSEL to a Microwave Reference." IEEE Transactions on Terahertz Science and Technology, vol. 13, no. 5, pp. 448-453, Sept. 2023. doi: 10.1109/TTHZ.2023.3280451.
4. Curwen, C. A., Kim, A. D., Karasik, B. S., Kawamura, J. H., Williams, B S., "Optical injection locking of a THz quantum-cascade VECSEL with an electronic source." Opt. Lett., vol. 48, pp. 3809-3812, 2023.
5. Devi, A., Gunapala, S.D., Premaratne, M., "Coherent and incoherent laser pump on a five-level atom in a strongly coupled cavity-QED system", (2022) Physical Review A, 105 (1), art. no. 013701. DOI: 10.1103/PhysRevA.105.013701
6. Ekanayake, U.N., Gunapala, S.D., Premaratne, M., "Engineered common environmental effects on multitransistor systems", (2023) Physical Review B, 107 (7), art. no. 075440. DOI: 10.1103/PhysRevB.107.075440
7. Ekanayake, U.N., Gunapala, S.D., Premaratne, M., "Stochastic model of noise for a quantum thermal transistor", (2023) Physical Review B, 108 (23), art. no. 235421. DOI: 10.1103/PhysRevB.108.235421
8. Femi-Oyetoro, J., Sypkens, S., LeDuc, H., Dickie, M., Beyer, A., Day, P., & Greer, F. (2023). Plasma-enhanced atomic layer deposition of titanium nitride for superconducting devices. arXiv preprint arXiv:2312.09984. https://doi.org/10.48550/arXiv.2312.09984.
9. Gottscholl, A., Cochrane, C. J., Kraus, H., "Operation Modes of an Optically Pumped 6H SiC Quantum/Solid-State Magnetometer," in IEEE Sensors Journal, vol. 24, no. 11, pp. 17596-17603, 1 June1, 2024, doi: 10.1109/JSEN.2024.3391191, https://dx.doi.org/10.1109/JSEN.2024.3391191.
10. Gunapala, S., Johnson, W., Ting, D., Soibel, A., Rafol, S., Keo, S., Pepper, B., Hill, C., Kalashnikova, O., Garay, M., Davies, A., Sood, A., Zeller, J., Lucey, P., Wright, R., Nunes, M., Babu, S., Ghuman, P., (2023). Applications of T2SL barrier infrared detectors in observational instruments. 25. 10.1117/12.2679191.
11. Guzman, P., Quine, C. M., Lohaus, S. H., Schul, L., Toda, R., Scott, V. J., Fultz, B.; A miniaturized piezoelectric Mössbauer spectrometer with feedback control. Rev. Sci. Instrum. 1 November 2023; 94 (11): 115107. https://doi.org/10.1063/5.0157651.
12. Hennessy, J., Rodriguez, R., West, W. C., Brandon, E. J., "Atomic layer deposition of calcium fluoride for barrier coating applications", JVST A 41, 042405 (2023). https://doi.org/10.1116/6.0002563.
13. Herath, K., Gunapala, S.D., Premaratne, M., "A Floquet engineering approach to optimize Schottky junction-based surface plasmonic waveguides", (2023) Scientific Reports, 13 (1), art. no. 10692. DOI: 10.1038/s41598-023-37801-x.
14. Herath, K., Gunapala, S.D., Premaratne, M., "Investigating the impact of polarization on surface plasmon polariton characteristics in plasmonic waveguides under periodic driving fields", (2024) Physica Scripta, 99 (4), art. no. 045014. DOI: 10.1088/1402-4896/ad3022.
15. Herath, K., Nirmalathas, A., Gunapala, S. D., Premaratne, M., "A Dual-Signaling Architecture for Enhancing Noise Resilience in Floquet Engineering-Based Chip-Scale Wireless Communication," in IEEE Journal on Selected Areas in Communications, vol. 42, no. 8, pp. 2039-2053, Aug. 2024, doi: 10.1109/JSAC.2024.3399206, https://doi.org/10.1109/JSAC.2024.3399206;
16. Herath, K., Nirmalathas, A., Gunapala, S.D., Premaratne, M., "Floquet engineering-based frequency demodulation method for wireless THz short-range communications", (2023) Physica Scripta, 98 (9), art. no. 095021. DOI:10.1088/1402-4896/aceebc.
17. Hoenk, M.E.; Jewell, A.D.; Kyne, G.; Hennessy, J.; Jones, T.; Shapiro, C.; Bush, N.; Nikzad, S.; Morris, D.; Lawrie, K.; et al. "Surface Passivation by Quantum Exclusion: On the Quantum Efficiency and Stability of Delta-Doped CCDs and CMOS Image Sensors in Space," Sensors 2023, 23, 9857. https://doi.org/10.3390/s23249857.
18. Hollenbach, M., Kasper, C., Erb, D., Bischoff, L., Hlawacek, G., Kraus, H., Kada, W., Ohshima, T., Helm, M., Facsko, S., Dyakonov, V., Astakhov, G. V., Ultralong-Term High-Density Data Storage with Atomic Defects in SiC. Adv. Funct. Mater. 2024, 34, 2313413. https://doi.org/10.1002/adfm.202313413.
19. Khanal, S., Rahiminejad, S., Lee, C., Kooi, Jacob W., Lin, R., Chattopadhyay, G., "A Waveguide-Based Variable Attenuator for Terahertz Applications." IEEE Transactions on Terahertz Science and Technology, vol. 14, no. 2, 2024. Publisher: IEEE.
20. Lien, M. R., Wang, N., Wenger, T., Wang, H., Gunapala, S. D., Povinelli, M. L., An All-Silicon Metalens Integrated with a Mid-Wave Infrared Black Phosphorus Photodiode. Adv. Optical Mater. 2024, 12, 2301952. https://doi.org/10.1002/adom.202301952 .
21. Mueller, A., Davis, S. I., Korzh, B., Valivarthi, R., Beyer, A. D., Youssef, R., Sinclair, N., Peña, C., Shaw, M. D., Spiropulu, M., "High-rate multiplexed entanglement source based on time-bin qubits for advanced quantum networks," Optica Quantum 2, 64-71 (2024).
22. Patel, S. R., Colangelo, M., Beyer, A. D., Taylor, G. G., Allmaras, J. P., Bumble, B., Wollman, E. E., Shaw, M. D., Berggren, K. K., Korzh, B.; Improvements of readout signal integrity in mid-infrared superconducting nanowire single-photon detectors. Appl. Phys. Lett. 15 April 2024; 124 (16): 162604. https://doi.org/10.1063/5.0202626.
23. Plazas Malagón, A. A., Shapiro, C., Choi, A., and Hirata, C., "Spot-based measurement of the brighter-fatter effect on a Roman Space Telescope H4RG detector and comparison with flat-field data", Journal of Instrumentation, vol. 19, no. 3, IOP, 2024. doi:10.1088/1748-0221/19/03/P03015.
24. Qiushi Guo et al, Ultrafast mode-locked laser in nanophotonic lithium niobate. Science 382, 708-713 (2023). DOI:10.1126/science.adj5438
25. Qiushi Z., Husker A., Zhan Z., Biondi E., Yin J., Civilini F., Costa L., Assessing the feasibility of Distributed Acoustic Sensing (DAS) for moonquake detection, Earth and Planetary Science Letters, Volume 635, 2024, 118695, ISSN 0012-821X, https://doi.org/10.1016/j.epsl.2024.118695.
26. Rafol, S. B., Gunapala, S. D., Ting, D. Z., Soibel, A., Khoshakhlagh, A., Keo, S. A., Pepper, B. J., Hill, C. J., Maruyama, Y., Fisher, A. M., Sood, A., Zeller, J., Wright, R., Lucey, P., Nunes, M., Flynn, L., Babu, S., Ghuman, P., "Long wavelength type-II superlattice barrier infrared detector for CubeSat hyperspectral thermal imager," Opto-Electronics Review 31, e144569 (2023).
27. Rahiminejad, S., van Berkel, S., Lin, R., Khanal, S., Jung-Kubiak, C., Chattopadhyay, G., Rais-Zadeh, M., "500-750 GHz Contactless Rotating MEMS Single-Pole Double-Throw Waveguide Switch," in Journal of Microelectromechanical Systems, doi: 10.1109/JMEMS.2024.3418335.
28. Roy, A., Ledezma, L., Costa, L. et al. Visible-to-mid-IR tunable frequency comb in nanophotonics. Nat Commun 14, 6549 (2023). https://doi.org/10.1038/s41467-023-42289-0.
29. Salama, M., Guthery, C., Chambouleyron, V., Jensen-Clem, R., Wallace, J. K., Delorme, J.-R., Troy, M., Wenger, T., Echeverri, D., Finnerty, L., Jovanovic, N., Liberman, J., López, R. A., Mawet, D., Morris, E. C., Kooten, M. van, Wang, J. J., Wizinowich, P., Xin, Y., & Xuan, J. (2024). Keck Primary Mirror Closed-loop Segment Control Using a Vector-Zernike Wavefront Sensor. The Astrophysical Journal, 967(2), 171. https://doi.org/10.3847/1538-4357/AD3B99.
30. Taylor, G. G., Walter, A. B., Korzh, B., Bumble, B., Patel, S. R., Allmaras, J. P., Beyer, A. D., O'Brient, R., Shaw, M. D., Wollman, E. E., "Low-noise single-photon counting superconducting nanowire detectors at infrared wavelengths up to 29 μm," Optica 10, 1672-1678 (2023).
31. Ting, D. Z., Soibel, A., Khoshakhlagh, A., Fisher, A. M., Pepper, B. J., Keo, S. A., Hill, C. J., Rafol, S. B., Gunapala, S. D., "Complementary Barrier Infrared Detector Architecture for Long-Wavelength Infrared InAs/InAsSb Type-II Superlattice," Appl. Sci. 12(24), 12508 (2022).
32. Ting, D. Z., Soibel, A., Khoshakhlagh, A., Keo, S. A., Rafol, S. B., Fisher, A. M., Hill, C. J., Pepper, B. J., Maruyama, Y., Gunapala, S. D., "InAs/InAsSb superlattice infrared detectors," Opto-Electronics Review 31, e144565 (2023).

33. Tran, M. T., Mora, M. F., Noell, A. C., Willis, P. A., "Protocol for Derivation of Amino Acids Using Dried Fluorescent Dye for In Situ Analysis", ACS Earth and Space Chemistry 2024 8 (1), 99-103, DOI: 10.1021/acsearthspacechem.3c00267.

34. van Berkel, S., Alonso-del Pino, M., Jung-Kubiak, C., Chattopadhyay, G., "An f/0.27 High-Gain Lens Antenna for Ultrasmall Platforms at THz Frequencies." IEEE Transactions on Terahertz Science and Technology, vol. 13, no. 5, 2023.

35. van Berkel, S., Rahiminejad, S., Lin, R., Chattopadhyay, G., "A 250–310 GHz Piezo-Motor Actuated SPDT Waveguide Switch With High Isolation." IEEE Transactions on Terahertz Science and Technology, vol. 13, no. 2, 2023. Publisher: IEEE.

36. Wijesekara, R.T., Gunapala, S.D., Premaratne, M., "Towards quantum thermal multi-transistor systems: Energy divider formalism", (2022) Physical Review B, 105 (23), art. no. 235412, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85132332080&doi=10.1103%2fPhysRevB.105.235412&partnerID=40&md5=1eaa291f55f6870f75fffc6e53385cd0, DOI: 10.1103/PhysRevB.105.235412.

37. Wright, R., Nunes, M. A., Lucey, P. G., Gunapala, S, Rafol, S., Ting, D., Ferrari-Wong, C., Flynn, L. P., George, T., "The HyTI mission," Proc. SPIE 12729, Sensors, Systems, and Next-Generation, Satellites XXVII, 1272906 (19 October 2023); doi: 10.1117/12.2679541.

38. Wu, Y., Curwen, C. A., Shahili, M., Reno, J. L., Williams, B. S., "RF Injection Locking of THz Metasurface Quantum-Cascade VECSEL." Laser and Photonics Reviews, 25 March 2023. https://doi.org/10.1002/lpor.202300007.

39. Yasar, F., Muller, R. E., Khoshakhlagh, A., Keo, S. A; Large-area fabrication of nanometer-scale features on GaN using e-beam lithography. J. Vac. Sci. Technol. B 1 March 2024; 42 (2): 022801. https://doi.org/10.1116/6.0003270.

40. Zhang, W., Kittlaus, E., Savchenkov, A., Iltchenko, V., Yi, L., Papp, S. B., Matsko, A. Monolithic optical resonator for ultrastable laser and photonic millimeter-wave synthesis, Communications Physics, 7(1), 177 (2024), https://doi.org/10.1038/s42005-024-01660-3.

41. Zhou, Y., Ruesink, F., Gertler, S., Cheng, H., Pavlovich, M., Kittlaus, E., ... & Rakich, P. "Nonreciprocal dissipation engineering via strong coupling with a continuum of modes." Physical Review X, 14(2), 021002 (2024). https://doi.org/10.1103/PhysRevX.14.021002.

Published Conference Publications

1. Azizi, A., Forouhar, S., Gunapala, S., Rafol, S, Soibel, A., Maruyama, Y., Keo, S., Ting, T., Vartanian, S., "Proton Radiation Effect on Barrier Infrared Detector Focal Plane Arrays," 2023 IEEE Radiation Effects Data Workshop (REDW) (in conjunction with 2023 NSREC), Kansas City, MO, USA, 2023, pp. 1-5.

2. Ballew, C., Roberts, G., Faraon, A., Inverse-designed volumetric meta-optics, Photonics Westc, San Francisco, CA, January (2023).

3. Ballew, C.; van Berkel, S.; Khanal, S.; Chattopadhyay, G., "Inverse-designed Volumetric Silicon Meta-optics." International Symposium on Space THz Technology, Charlottesville, VA, March (2024).

4. Briggs, R. M., Fradet, M., Ruff, G. A., Results from the Combustion Product Monitor on the Saffire VI Spacecraft Fire Safety Experiment, 53rd International Conference on Environmental Systems, Louisville, KY, July (2024).

5. Chattopadhyay, G., Compact and Low-Power Terahertz Instruments for Space Applications, 2023 IEEE Radio and Antenna Days of the Indian Ocean (RADIO), Publisher: IEEE, Balaclava, Mauritius, May (2023).

6. Costa, L., Varughese, S., Mertz, P., Kamalov, V., Zhan, Z., Localization of Seismic Waves in Submarine Fiber Optics using Polarization Only Measurements, SubOptic Sensing Working Group Meeting, April (2024).

7. Curwen, C. A., Fradet, M., Briggs, R. M., Scanning OF-CEAS technique with simple configuration and high spectral resolution, Jet Propulsion Laboratory, California Institute of Technology, 2023.

8. Femi-Oyetoro, J., Sypkens, S., LeDuc, H., Dickie, M., Beyer, A., Day, P., & Greer, F., Atomic layer deposition of superconducting titanium nitride for through-silicon-via structures and photon detection. In American Vacuum Society 69th International Symposium & Exhibition, Portland, OR, November (2023). https://avs69.avs.org/wp-content/uploads/2023/07/Technical-Program.pdf.

9. Greer, F., Atomic Scale Processing and Surface Engineering to Maximize Microdevice Performance for Remote Sensing and Imaging Applications, In American Vacuum Society 69th International Symposium & Exhibition (Invited), Portland, OR, November (2023).

10. Gu, Y., Zheng, T., Kwon, H., Ballew, C., Roberts, G., Faraon, A., Low-voltage Dynamic Light Manipulation with Slot Silicon-organic Metasurfaces, 2023 Conference on Lasers and Electro-Optics (CLEO), Publisher: IEEE, San Jose, CA, May (2023).

11. Gunapala, S., Johnson, W., Ting, D., Soibel, A., Rafol, S., Keo, S., Pepper, B., Hill, C., Kalashnikova, O., Garay, M., Davies, A., Sood, A., Zeller, J., Lucey, P., Wright, R., Nunes, M., Babu, S., Ghuman, P., "Applications of T2SL barrier infrared detectors in observational instruments," Proc. SPIE 12729, Sensors, Systems, and Next-Generation Satellites XXVII, (Invited) 127290Q (19 October 2023); https://doi.org/10.1117/12.2679191.

12. Gunapala, S., Johnson, W., Ting, D., Soibel, A., Rafol, S., Keo, S., Pepper, B., Hill, C., Kalashnikova, O., Garay, M., Davies, A., "Compact Fire Infrared Radiance Spectral Tracker (c-FIRST)," ESA 4S (Small Satellite Systems and Services) Symposium, Palms De Mallorca, Spain, May (2024).

13. Gunapala, S., Johnson, W., Soibel, A., Ting, D., Ramsey, P., Kalashnikova, O., Garay, M., Davies, A., Maruyama, Y., Rafol, S., Sood, A., Zeller, J., David, C., Babu, S., Ghuman, P., "Compact Fire Infrared Radiance Spectral Tracker (c-FIRST)," NASA Earth Science Technology Forum, Crystal City, VA, June (2024). (https://esto.nasa.gov/forums/estf2024/estf24Abstracts/gunapala.html).

14. Gunapala, S., Ting, D., Johnson, W., Soibel, A., Ramsey, P., Kalashnikova, O., Garay, M., Davies, A., Maruyama, Y., Fisher, J., Sood, A., Zeller, J., David, C., Babu, S., Ghuman, P., "Towards compact fire infrared radiance spectral tracker (c-FIRST)", Proceedings Volume 12425, Smart Photonic and Optoelectronic Integrated Circuits 2023; 1242509 (2023).

15. Gunapala, S., Ting, D., Rafol, S., Soibel, A., Khoshakhlagh, A., Keo, S., Pepper, B., Fisher, A., Hill, C., Sood, A., Zeller, J., Lucey, P., Wright, R., Nunes, M., Flynn, L., Babu, S., and Ghuman, P., "Development of T2SLS LWIR focal plane arrays for the hyperspectral thermal imager (HyTI)", Proc. SPIE 12777, International Conference on Space Optics — ICSO 2022, 127773O (12 July 2023).

16. Harrysson Rodrigues, H. I., AlGaN/GaN HEMTs with submicron gates for high-frequency operation in harsh space environments, In American Vacuum Society 69th International Symposium & Exhibition, Portland, OR, November (2023).

17. Husker, A. L., Zhai, Q., Zhan, Z., Civilini, F., Pereira da Costa, L. D., Yin, J., Tamama, Y., Assessing the Feasibility of Distributed Acoustic Sensing (DAS) for Moonquake Detection on the Lunar Surface, AGU23 Fall Meeting, San Francisco, CA, December (2023).

18. Lee, T., Gupta, R., Krishnaswamy, H., Gargini, P., McCune, E., Chang, H., Valdes-Garcia, A., Samantha, K., Sengupta, K., Ur-Rehman, M., Mehdi, I., mmWAVE and Signal Processing, 2023 IEEE Future Networks World Forum (FNWF), Baltimore, MD, November (2023).

19. Maestrini, A., Siles, J., Lee, C., Lin, R., Philip, L., Mehdi, I., 2 THz Receiver for Thermospheric Science with 7000K DSB Noise Temperature at Room Temperature, 2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Publisher: IEEE, Montreal, Quebec, Canada, September (2023).

20. Mertz, P., Liu, M., Hu, Y., Edirisinghe, S., Costa, L., Varughese, S., Zhan, Z., Kamalov, V., Sensing and Localizing Tidal Variations on a Submarine Communications Cable Using RF-OTDR, IEEE Photonics Society Summer Topicals Meeting Series (Invited), Bridgetown, Barbados, July (2024).

21. Nejadriahi, H., Kittlaus, E., Low loss silicon nitride for application in cold atom sensors, Proceedings Volume 12646, Metamaterials, Metadevices, and Metasystems; 1264605, SPIE Optics + Photonics, San Diego, CA, August (2023).

22. Rahiminejad, S., van Berkel, S., Lin, R. H., Jung-Kubiak, C., Chattopadhyay, G., Rais-Zadeh, M., Robust MEMS Waveguide Switch for THz Spectroscopy in Space, 2023 22nd International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers), Publisher: IEEE, Kyoto, Japan, June (2023).

23. Rais-Zadeh, M., MEMS and Microsystems for Space Environment, International Mechanical Engineering Congress & Exposition (Featured Speaker), New Orleans, LA, October 30, (2023).

24. Ruane, G., Wallace, J. K., Riggs, A. J. E., Wenger, T., Bagheri, M., Jewell, J., Raouf, N., Allan, G., Mejia Prada, C., Noyes, M., Walter, A. B., Dual purpose Lyot coronagraph masks for simultaneous high-contrast imaging and high-resolution wavefront sensing, SPIE Optical Engineering + Applications, Proc. Volume 12680, Techniques and Instrumentation for Detection of Exoplanets XI, 1268018, San Diego, CA, October (2023). https://doi.org/10.1117/12.2676853.

25. Soibel, A., Ting, D. Z., Rafol, S. B., Keo, S. A., Khoshakhlagh, A., Hill, C. J., Pepper, B. J., Fisher, A. M., Gunapala, S. D, "Infrared sensors for monitoring of Earth's surface and atmosphere," Proc. SPIE PC12835, Optical Fibers and Sensors for Medical Diagnostics, Treatment, and Environmental Applications XXIV, PC128350C, Presented at SPIE BiOS (Keynote): January 28, 2024; Published March 13 (2024); https://doi.org/10.1117/12.3009067.46c6be7d-1145-ee11-a99c-00505691c5e1.

26. Sood, A. K., Zeller, J. W., Ghuman, P., Babu, S., Gunapala, S., Soibel, A., Ting, D., Chaudhary, L. S., Efstathiadis, H., "Advanced nanostructured antireflection coatings for high performances IR detector and imaging applications," SPIE Proceedings Volume 12514, Image Sensing Technologies: Materials, Devices, Systems, and Applications X; 125140F (2023).

27. Sood, A. K., Zeller, J. W., Ghuman, P., Babu, S., Soibel, A., Ting, D., Gunapala, S., Chaudhary, L., Efstathiadis, H., "Advanced MWIR and LWIR band detection and imaging with nanostructured antireflection coating technology," SPIE Proceedings Volume 12687, Infrared Sensors, Devices, and Applications XIII; 1268704 (2023).

28. van Berkel, S.L., Maestrini, A., Jung-Kubiak, C., Bosma, Sjoerd, Alonso-del Pino M., Hayton, D. Kooi, Jacob; Siles, J. V., Llombart, N, Quasi-Optical LO Coupling Validation for a Planarly Integrated 2 × 2 Pixel Heterodyne Array at 1.95 THz, 2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Publisher: IEEE, Montreal, Quebec, Canada, September (2023).

29. van Berkel, S., Rahiminejad, S., Lin, R., Chattopadhyay, G., A 250–310 GHz Piezo-Motor Actuated SPDT Waveguide Switch With High Isolation, IEEE Transactions on Terahertz Science and Technology, vol. 13, no. 2, Publisher: IEEE (2023).

30. Wenger, T., Wallace, J.K., Ruane, G., Jewell, J., Riggs, A. J. E., Raouf, N., Design and fabrication of metasurfaces for wavefront sensing and high-contrast imaging in the visible, SPIE Nanoscience + Engineering, Proc. Volume 12646, Metamaterials, Metadevices, and Metasystems 2023, 1264604, San Diego, CA, October (2023). https://doi.org/10.1117/12.2677961

31. Wright, R., Nunes, M. A., Lucey, P. G., Gunapala, S., Rafol, S., Ting, D., Ferrari-Wong, C., Flynn, L. P., George, T., "The HyTI mission", SPIE Proceedings Volume 12729, Sensors, Systems, and Next-Generation Satellites XXVII; 1272906 (2023).

32. Yasar, F. et al, Spectral Dynamics in GaN Photonic Crystal Scintillators: Elucidating Optical Responses Across UV, X-ray, and Alpha Radiation, 17th International Conference on Scintillating Materials and their Applications (SCINT2024), Milan, Italy, July (2024).

First Author Papers

1. "Performance of the SPARCS UV camera and detectors," April Jewell et al., Paper ID 13093-3.

2. "Quantum efficiency of delta-doped CCD201-20 detectors for sub-orbital and space missions" Gillian Kyne et al., Paper ID 13093-158.

3. "Atomic layer processing as a platform for ultraviolet coatings," John Hennessy, Paper ID 13100-231.

4. "Superlattice-doped PMOS Imaging Arrays for Broadband Visible Applications," April Jewell et al., Paper ID 13103-39.

5. "Delta-doped FUV, NUV, and UV/optical CMOS imagers for exoplanet science, astrophysics and time domain astronomy," Michael Hoenk et al., Paper ID 13103-44.

Co-Author Papers

1. "Aspera Payload Design Overview: UV SmallSat Mission to Detect and Map Warm-hot Halo Gas around the Nearby Galaxies," H. Chung et al., Paper ID 13093-1.

2. "FIREBall-2(023): the 2023 flight of the Faint Intergalactic-medium Redshifted Emission Balloon," D. Miles et al., Paper ID 13093-2.

3. "UVEX: The Ultraviolet Explorer," F. Harrison et al., Paper ID 13093-14

4. "The Initial Design Of Maratus: A 12U Narrowband Imager for Mapping the Circumgalactic Medium," S. Tuttle et al., Paper ID 13093-16.

5. "The UVIa 12U CubeSat concept: mission overview," K. Hoadley et al., Paper ID 13093-17.

6. "Development of broadband and narrowband coatings for future UV missions: increasing throughput, uniformity, and environmental stability in the far- and Lyman-ultraviolet," K. France et al., Paper ID 13093-22.

7. "Advancing Ultraviolet Detector Technology for future missions: Investigating the dark current plateau in silicon detectors using photon-counting EMCCDs," A. Khan et al., Paper ID 13093-29.

8. "FIREBall-2 2023: flight communications performance," G. Davis et al., Paper ID 13093-104.

9. "Realignment and performance verification of two-mirror focal corrector optics for FIREBall-2 using computer generated hologram (CGH)," S. Agarwal et al., Paper ID 13093-107.

10. "Observing modes of the SPRITE 12U CubeSat: a probe of star formation feedback with far-UV imaging spectroscopy," D. O'Sullivan et al., Paper ID 13093-114.

11. "Preflight characterization of the SPRITE CubeSat: a far-UV imaging spectrograph for stellar feedback in local galaxies," M. Bowen et al., Paper ID 13093-116.

12. "Assembly, integration, and testing of the Star-Planet Activity Research CubeSat (SPARCS)," L. Jensen et al., Paper ID 13093-119.

13. "Photometric calibration in the ultraviolet of the Star-Planet Activity Research CubeSat (SPARCS)," D. Ardila et al., Paper ID 13093-120.

14. "Nox: a SmallSat mission concept for characterizing all-sky Lyman-UV background," H. Chung et al., paper ID 13093-135.

15. "The optical design of the UVIa CubeSat: a multi-channel ultraviolet telescope for transient science," F. Cruz Aguirre et al., Paper ID 13093-136.

16. "Aluminum-based mirrors with an aluminum fluoride protective coating: A comparative study of small and large-scale atomic layer deposition systems," S. Tornøe et al., Paper ID 13100-10.

17. "Improving endurance and spectral responses of protected telescope mirrors by implementing sputtering atomic layer augmented deposition (SALAD): Two case studies—silver and aluminum-based protected mirrors," S. Tornøe et al., Paper ID 13100-134.

18. "Characterization and validation of next generation image sensors for outer space," N. Shade et al., Paper ID 13103-45.

Awards and Recognition by External Organizations

1. Gottscholl, A., Kraus, H., Dr. Andreas Gottscholl and Dr. Hannes Kraus' work on quantum solid state magnetometer instrument development was featured in this week's (Jun 4 2024) NASA Planetary Science Division news highlights. The article, titled "Solid State Quantum Magnetometers—Seeking out water worlds from the quantum world", is available on the public NASA science website.

2. Jewell, A., April Jewell was elected Chair of the Thin Film Division (TFD) of the American Vacuum Society (AVS).

3. Knehr, E., Emanuel Knehr won the "best poster" award for Engineering and Technology at the Postdoc Research Conference at JPL. There was an award ceremony attended by Dr. Leshin, Sue Owen, and many others from JPL, and he gave a 15-minute presentation on his research.

4. Rais-Zadeh, M., Dr. Mina Rais-Zadeh has been honoured with a Fellowship by the Institution of Engineering and Technology (IET).
5. Rais-Zadeh, M., January 2024: The IEEE MEMS international steering committee has selected Dr. Mina Rais-Zadeh (JPL-389R) and Prof. Hanseup Kim (U. of Utah) as General Chairs of the IEEE MEMS conference in 2027.
6. Shanks, D., Daniel Shanks and Garreth Ruane (383A) received the Voyager award from the Exoplanet Exploration Program Office and Astronomy and Physics Directorate for their work developing a segmented mirror with sub-nm phase steps to enable coronagraph testing with segmented primary mirror pupils.
7. Shaw, M., Matt Shaw has begun a 3-year appointment as an Associate Editor for Optica, a leading journal in the optics and photonics community.
8. Tallarida, N., Nicholas Tallarida from the Flight Imaging Systems Group (389N) received the Charles Elachi Award for major contributions in optomechanical design and testing of flight subsystems and novel ray-tracing, thermal-mechanical analysis of R&D tasks.
9. Wollman, E., The DSOC project has met some of its key requirements and has successfully downlinked data at the highest data rate the system is designed for, 267 Mbps. This was acheived at a range of 0.17 AU as the spacecraft makes its way toward Psyche. We also successfully downlinked a "cat video" which was the subject of a JPL press release. This has been picked up by several major news outlets including CNN and the BBC, and Emma Wollman was interviewed for a story on NPR.
10. Wollman, E., Emma Wollman from the Superconducting Materials And Devices received the Lew Allen Award for outstanding record of innovation in superconducting nanowire single photon detectors and their implementation in the DSOC project.

New Technology Reports

1. Briggs, R. M., Fradet, M., Tallarida, N. R., Christensen, L. E., "High-Dynamic-Range Laser Absorption Spectrometer for Detector of Water in Oxygen Gas", NTR 53043.
2. Curwen, C. A., Briggs, R. M., Fradet, M., "Optical-Feedback Cavity Enhanced Absorption Spectrometer", NTR 52763.
3. Femi-Oyetoro, J., Greer, F. Atomic layer deposition of superconducting transition metal nitrides for quantum circuits and detectors. NTR 52669, 52965, CIT 9052-P. Filed: 08/02/2024.
4. Femi-Oyetoro, J., Greer, F., Beyer, A., LeDuc, J., (2024) Atomic layer etching for precision fabrication of aluminum-based superconducting and quantum devices. NTR 53193.
5. Nejadriahi, H., September 2023, "Integrated Narrow-Linewidth External Cavity Laser (ECL) Using Low Loss Silicon Nitride (Si3N4)," NTR 52843.
6. Nejadriahi, H., " photonic Self-Referenced Interferometer," NTR 52966.
7. Wenger, T., Drouin, B.,"Spectropolarimetric UV metagrating, NTR 53107.

Patents

1. Costa, L., Marandi, A., Zhan, Z., Multimode transmission distributed optical fiber sensor. 2023/10/5.
2. Femi-Oyetoro, J., & Greer, F., Atomic layer deposition of superconducting transition metal nitrides for quantum circuits and detectors. CIT 9052-P. Filed: 08/02/2024.
3. Fradet, M., Tosi, L. P., Rais-Zadeh, M., Sherrill, K. V., Modarress, D., Svitek, P., Modarress Ruby, K., "Laser Doppler Velocimetry-Based Flow Sensor for Downhole Measurements in Oil Pipes" US 2024/0125636 A1 April 18, 2024.
4. Fradet, M., Briggs, R. M., Islam, K. M., "Spectroscopy Device Incorporating a Mid-Infrared Laser", US 2023/0408406 A1 December 21, 2023.
5. Sherrit, S., Tosi, L. P., Sherrill, K. V., Rais-Zadeh, M., Hall, J. L., Fradet, M., Briggs, R. M., Yahnker, C. R., "System for measuring multiphase flow in downhole conditions and flow regimes", US 2024/0229643 A1 July 11, 2024.

MDL Equipment Complement

Material Deposition

- Electron-Beam Evaporators (7)
- Angstrom E-beam/Radak Evaporator
- AJA UHV E-beam Evaporator
- Sloan E-Beam Evaporator
- TSC E-Beam Evaporator
- Veeco E-Beam Evaporator
- Xiron E-Beam Evaporator
- Temescal E-Beam Dielectric Evaporator
- Temescal E-Beam Evaporator for IR detector metallizations
- Thermal Evaporators (4)
  - KJL Indium Evaporator
  - Denton Indium Evaporator
  - SIO Evaporator (temporarily decommissioned)
  - CHA Aluminum Evaporator
- AJA Load Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- AJA Dielectric Sputtering System
- AJA Metal Sputtering System
- Hummer Sputter System
- 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 and PTIQ Software Upgrade.
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Beneq TFS-200 Atomic Layer Deposition (ALD) System with Meaglow plasma source upgrade
- Thermal Evaporation Enhanced-ALD 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
- Themco Wet/Dry Silicon oxidation manual Furnaces
- 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)
- Lesker #1 Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (SIS)
- Lesker #2 Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (SIS)
- Lesker Silicon Dioxide Sputter (Low Loss Dielectric) UHV Sputtering system (SIS)

Lithography

- JEOL JBX9500FS Electron-Beam (E-beam) Lithography system with a 3.6-nm spot size, switchable 100,000 & 48,000-volt acceleration voltages, ability to handle wafers up to 9 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 10 mm of sag
- Heidelberg MLA 150 Maskless Aligner (200mm square) with 375nm, 405nm, die x die alignment, and gray scale modes (1.0-µm res.)
- Heidelberg MLA 150 Maskless Aligner (150mm square) with 375nm, 405nm, and gray scale modes (1.0-µm res.)
- Canon FPA3000 i4 i-Line Stepper (0.35-µm res.)
- Canon FPA3000 EX3 Stepper with EX4 Optics (0.25-µm res.)
- Canon FPA3000 EX6 DUV Stepper (0.18-µm res.)
- Future ASML PAS 5500-1150C ArF Lithography System (with 0.09 µm resolution to 0.065 µm with off-axis illumination).
- Karl Suss MJB3 with backside IR Contact Aligners:
  - Suss MA-6 (UV300) with MO Exposure Optics upgrade
  - Suss BA-6 (UV400)

Resist Process

- Site Services Tractix Wafer Track Wafer resist Coater/Developer Dispense Systems:
  - Suss Gamma 4-Module Resist Coater/ Developer System
  - SolarSemi MC204 Microcluster Resist Coating System
- Osiris/Solitec/Headway manual resist coaters (5)
- Sonotek Exacta-Coat E1027 Photoresist Spray Coater
- Thermal Bake Vacuum ovens, Hotplates, Convection Ovens (16)
- Yield Engineering System (YES) Reversal Oven

Dry Etching/Ashing

- Commonwealth IBE-80 Ion Mill
- YES Eco-Clean Downstream Plasma Asher
- Branson Plasma Asher
- Tepla PP300SA Microwave Plasma Asher
- Reactive Plasma Etch (Fluorine/ Chlorine, ICP, ALE, DRIE, RIE)
- 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 Oxygen RIE for Superconductors
- Samco Oxygen RIE
- Custom XeF2 Etcher
- Oxford PlasmaPro 100 Cobra Load-Locked Cryo Etching / Atomic Layer Etching / Bosch Etching System, primarily for Black Silicon.
- Unaxis Shuttleline Load-Locked Chlorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm Versaline Chlorine-based ICP Etcher
- Future Oxford Cobra Load-Locked Inductively Coupled Plasma with Cryo and Atomic Layer Etching capabilities for Chlorine and Bromine-based Etches

Wet Etching & Sample Preparation

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (5), including (1) dedicated for batch processing of 6" wafers
- Modutek Solvent bench with multi-frequency ultrasonic and mega-sonic baths
- S-cubed high Pressure Spray Liftoff and Photoresist removal tool
- Semitool 870S Dual Spin Rinser Dryer for Silicon Wafers (2)
- Wet Chemical Hoods (7)
- Acid Wet Processing Benches (5)
- Photoresist Developer Bench
- KOH/TMAH Bench
- Jelight UVO-Cleaners (2)
- Novascan UV Ozone Ultraviolet Light Ozone Cleaner
- Tousimis 915B Critical Point Dryer
- Solaris 150 Rapid Thermal Processor
- Polishing and Planarization Stations (4)
- Strasbaugh 6EC Chemical Mechanical Polisher
- Allied Tech polishing Stations for GaAs FPA thinning
- 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 UV-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
- EVG 520Is Semi-Automatic Wafer Bonding System for fusion and anodic bonding of Si wafers up to 200mm
- Electronic Visions AB1 Wafer Bonder
- EVG 520Is Semi-Automatic Wafer Bonding System for adhesive bonding with organic materials such as BCB
- Finetech Fineplacer 96 "Lambda" Bump Bonder
- Thinning Station and Inspection Systems for CCD Thinning
- West Bond Wire Bonder
- DISCO 320 and 321 Wafer Dicers (2)
- Tempress Scriber
- SEC Pick and Place tool
- Loomis LSD-100 Scriber Breaker
- Tosok GD-300 Die Bonding
- Ultimaker S5 3D printer

Characterization

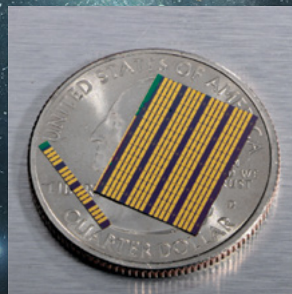
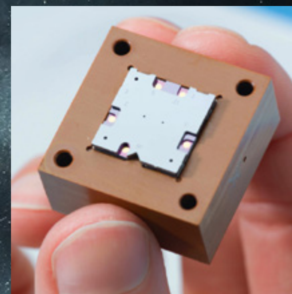
- Profilometers (2) (Dektak XT-A and Alphastep 500)
- Frontier Semiconductor FSM 128-NT (200-mm/8-inch) Film Stress and Wafer Bow Mapping System
- LEI 1510 Contactless Sheet Resistance Tool
- Hitachi Regulus 8230 UHR Cold Field Emission Scanning Electron Microscope (SEM) with Aztec Energy Dispersive X-ray Microanalysis System and Critical Dimension Measurement capabilities.
- Jandel Model RM3000+ 4-Point Probe System
- FISBA µPhase 2 HR Compact Optical Interferometer
- Woollam RC2 Ellipsometer
- CPX Cryo-Probe Station Lakeshore Cryotronics 1.7 Kelvin Cryo Probe Station
- Bluefors Cryogen-Free Dilution refrigerator
- 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 Automated Thin-Film Thickness Mapper
- Bruker Dimension 5000 Atomic Force Microscope (AFM)
- Park Systems Inc. NX20 Atómic Force Microscope (AFM)
- KLA-Tencor Surfscan 6200 Surface Analysis System Wafer Particle Monitor with upgraded Software (2)
- 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
- Rame-hart contact angle measurement
- 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
- Veeco FFP 100 4-Point Probe

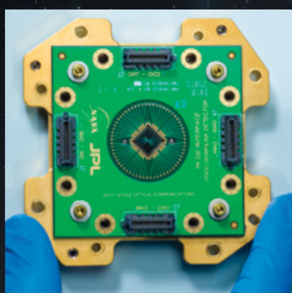
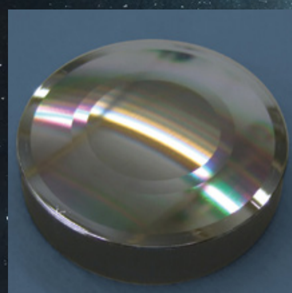
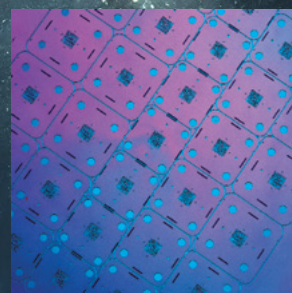
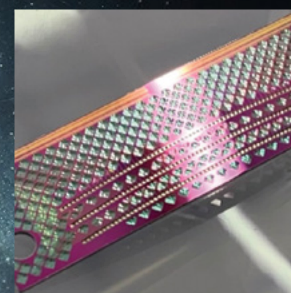
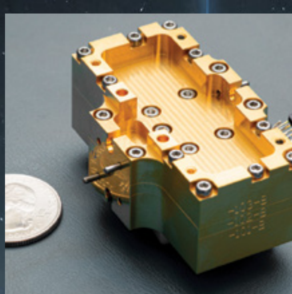
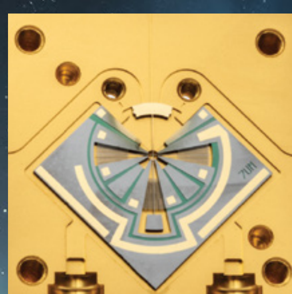
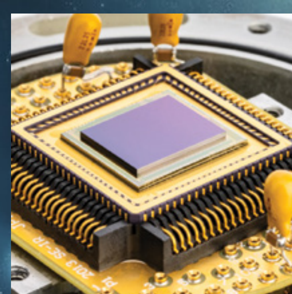
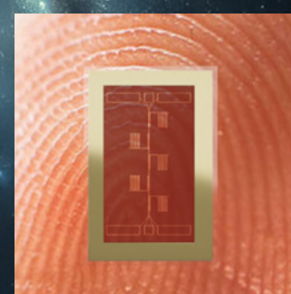
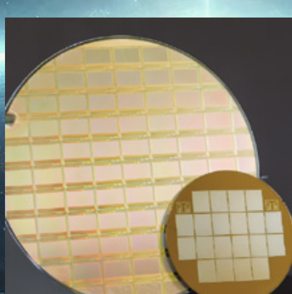
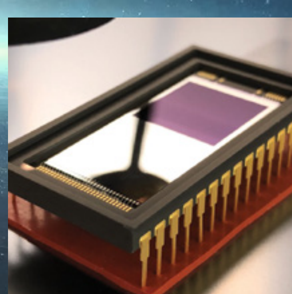
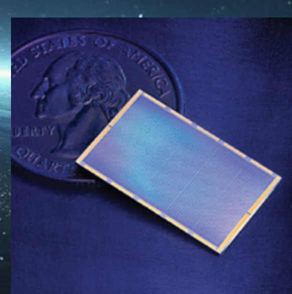
THIS IS MDL

THE PIONEERING CONTRIBUTIONS OF MDL ARE A TESTAMENT TO THE HARD WORK AND DEDICATION OF ITS REMARKABLE TEAM OF SCIENTISTS, TECHNOLOGISTS, AND RESEARCH PERSONNEL.

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

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


National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.microdevices.jpl.nasa.gov

www.nasa.gov

CL#25-0428   JPL 400-1756 03/25