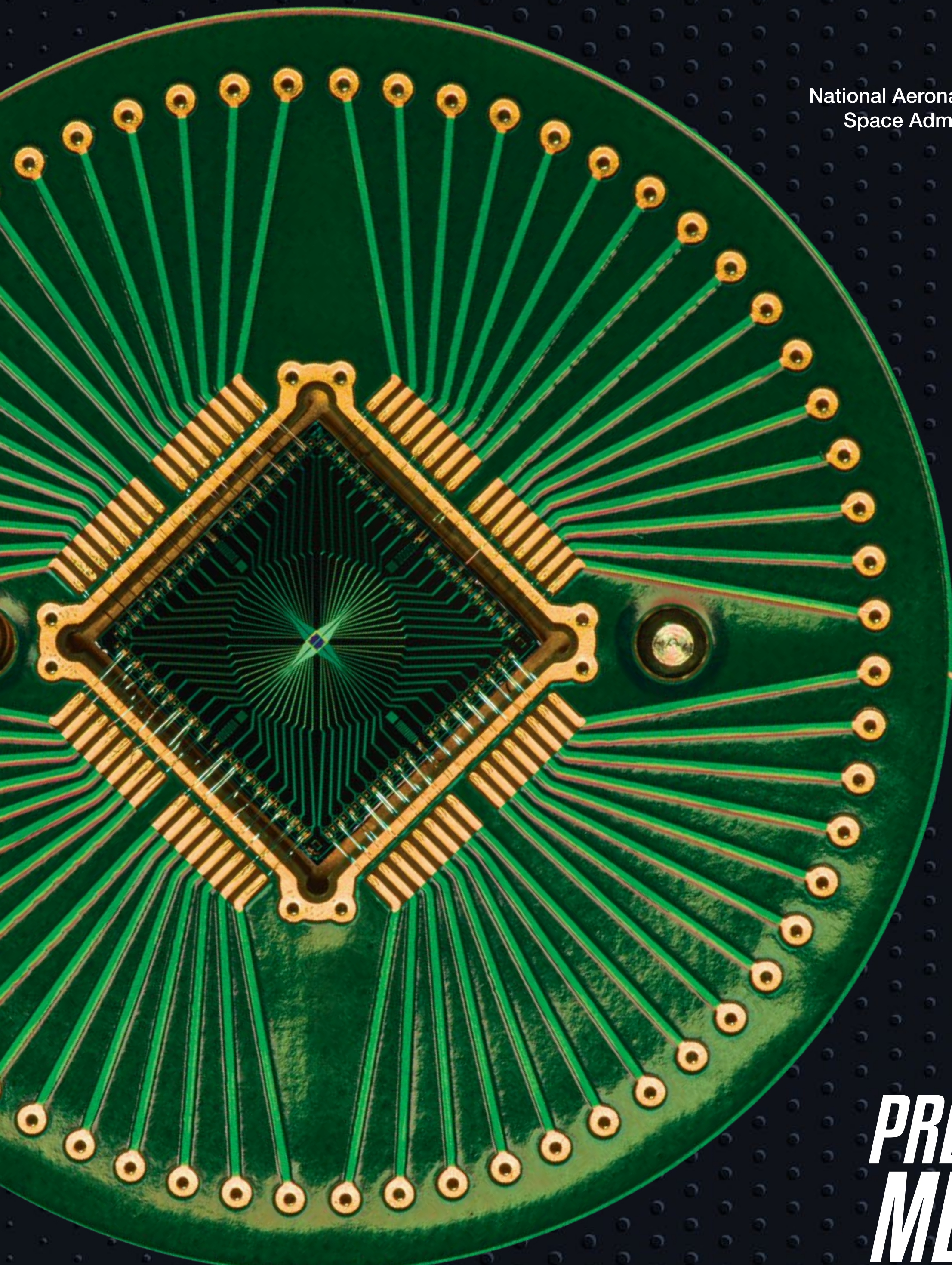

National Aeronautics and Space Administration

PREPARING MDL TO SUPPORT NASA INTO THE FUTURE

Jet Propulsion Laboratory
California Institute of Technology

MICRODEVICES LABORATORY
2023 | ANNUAL REPORT

The EMIT mission studies the composition of surface minerals in Earth's arid regions, helping climate researchers better understand how dust affects climate when it is blown into the atmosphere.

JPL DIRECTOR'S MESSAGE

At JPL, our north star is to drive the forefront of scientific discovery and extraordinary benefit to humanity through our groundbreaking missions, innovative technology and first-of-a-kind research. The Microdevices Laboratory (MDL) is a unique embodiment of this. A pioneering team, MDL invents, develops and delivers cutting-edge technology and novel microdevices that enable new instruments and missions for NASA, and that help us better understand space and our home planet.

This past year, MDL successfully delivered devices for space missions in development for Earth, Planetary Science, Astrophysics and more. They enabled elements of the two deformable mirrors on the Coronagraph Instrument (CGI) of the Roman Space Telescope, critical components that compensate for tiny flaws and changes in the telescope's optics.

NASA missions today are also receiving first-of-their-kind measurements enabled by devices developed by MDL. For example, measurements on the surface of Mars from the Planetary Instrument for X-ray Lithochemistry (PIXEL) and Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC) instruments rely on unique MDL components. The new mineral maps from the imaging spectroscopy of the Earth Surface Mineral Dust Source Investigation (EMIT) mission are enabled by an MDL invented grating, slit, and light trap. The James Webb Space Telescope (JWST) Near Infrared Camera (NIRCam) coronagraph uses MDL electron beam fabricated occulting masks to see planets orbiting distant stars.

As true pioneers, the MDL team remains focused on developing next generation devices that will support the future needs of NASA and benefit our nation, and beyond. To achieve this, JPL is investing in nurturing existing talent, bringing the best and brightest minds on board, and supporting specialized MDL equipment and its optimized facilities.

Congratulations to the MDL team on their exceptional achievements and for enabling JPL to have an expanded impact on the space ecosystem for decades to come.

LAURIE LESHIN

Director, Jet Propulsion Laboratory

For the past 33 years, through the dedication and hard work of many talented scientists, technologists, and research staff, JPL's Microdevices Laboratory (MDL) has made fundamental contributions to diffractive optics, detectors, nano- and microsystems, lasers, focal planes with breakthrough sensitivity from deep UV to submillimeter, life detection in extreme environments, and MEMS. Through this research and development, MDL has produced novel, innovative, and unique components and subsystems enabling remarkable achievements in support of NASA's missions and other national priorities. We are excited to have been a part of this important work and look forward to many years of continued success.

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

The EMIT team launched the instrument on a SpaceX resupply mission on July 14, 2022.

MDL DIRECTOR'S MESSAGE

In support of NASA, the Microdevices Laboratory (MDL) is chartered to invent, develop, and deliver novel microdevices and critical microdevice technologies not available elsewhere that enable new observations, capabilities, instruments, and missions. MDL has a three-decade track record of fulfilling this charter. Looking forward, MDL is committed to continuing and expanding upon this focus for NASA, delivering access to new observables while reducing the cost of missions through next-generation microdevices with reduced size, mass, and power.

To ensure alignment with our charter, the MDL Visiting Committee held a two-day review this past year, assessing the quality and relevance of MDL's scientific/technical research and device developments for NASA and evaluating the equipment and facilities and their relevance looking to the future. We have received the Committee's report and are grateful for their input. We are now working to implement their actionable recommendations, especially their key recommendation to focus on MDL's talent and infrastructure to prepare for the next decade and beyond.

I wish to express my awe and gratitude to the people of MDL for their hard work, intellectual excellence, and exceptional achievements over the past year. This Annual Report records a snapshot of the activities at MDL and highlights elements of the people and projects involved at all levels of technology development, from early concepts to delivery for space missions. I hope you will find the contents interesting. Please reach out to us if you see opportunities for expanded collaboration in support of NASA's Science, Exploration Systems Development, and Space Technology Directorates.

ROBERT O. GREEN

Director, Microdevices Laboratory

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As we look back and summarize our 2022 activities, it is worth noting that we are also in the middle of a new and exciting period for JPL. A guiding document, *"Dare Mighty Things Together: A Plan for JPL 2023 – 2026,"* has just been published. In it, three main goals are outlined:

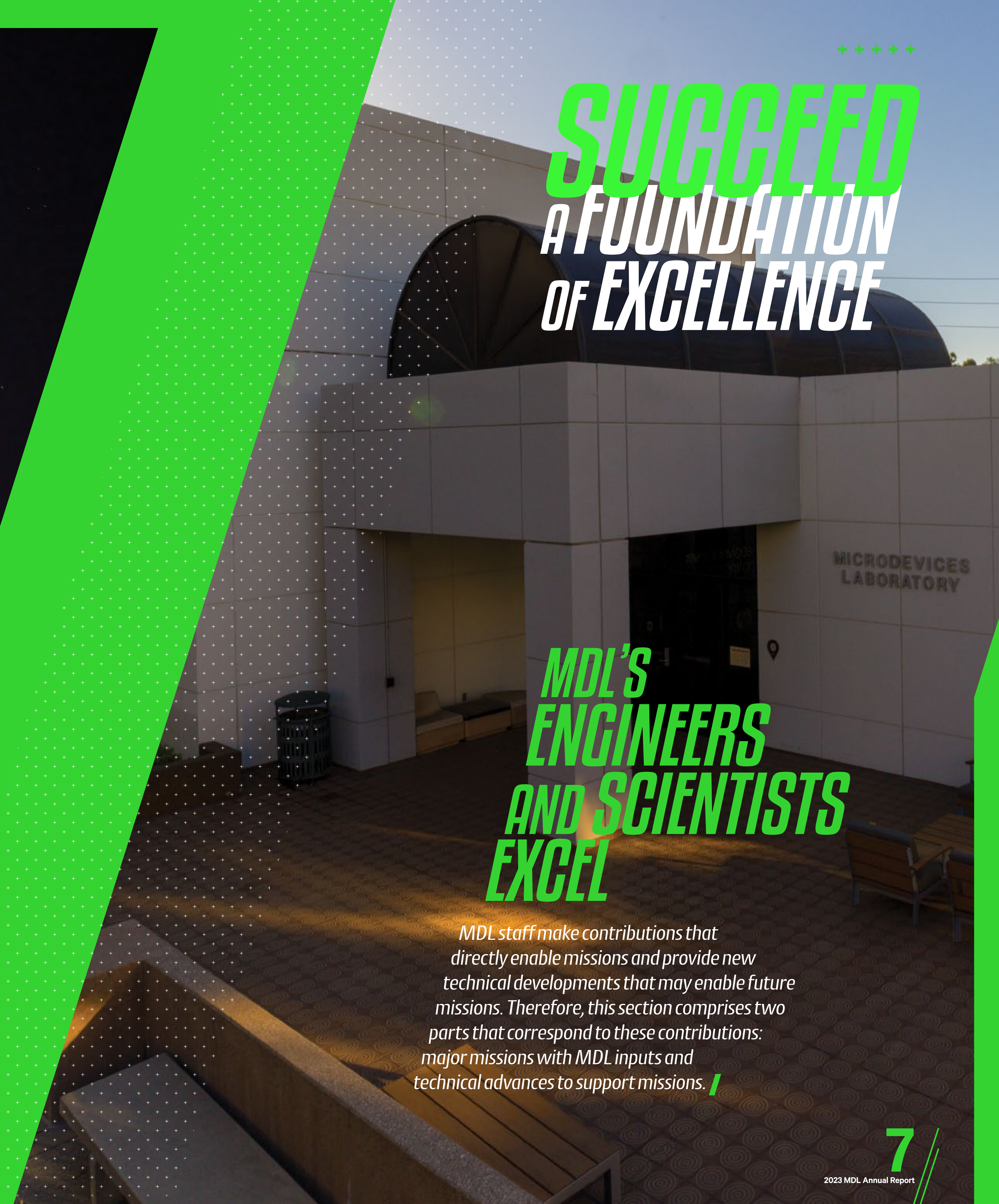
- **SUCCEED** — ADVANCE SCIENCE AND EXPLORATION BY DELIVERING ON OUR COMMITMENTS
- **SEED** — GROW OUR CAPABILITIES TO ENABLE THE FUTURE OF SCIENTIFIC EXPLORATION FROM SPACE
- **LEAD** — BE AN INSPIRING ROLE MODEL AND ENABLING INDUSTRY LEADER

MDL IS ENERGIZED BY THESE CHALLENGES

Even within MDL's 2022 activities, there are already areas where, with continuing effort, we might aspire to Dare Mighty Things Together with teams within and outside JPL.

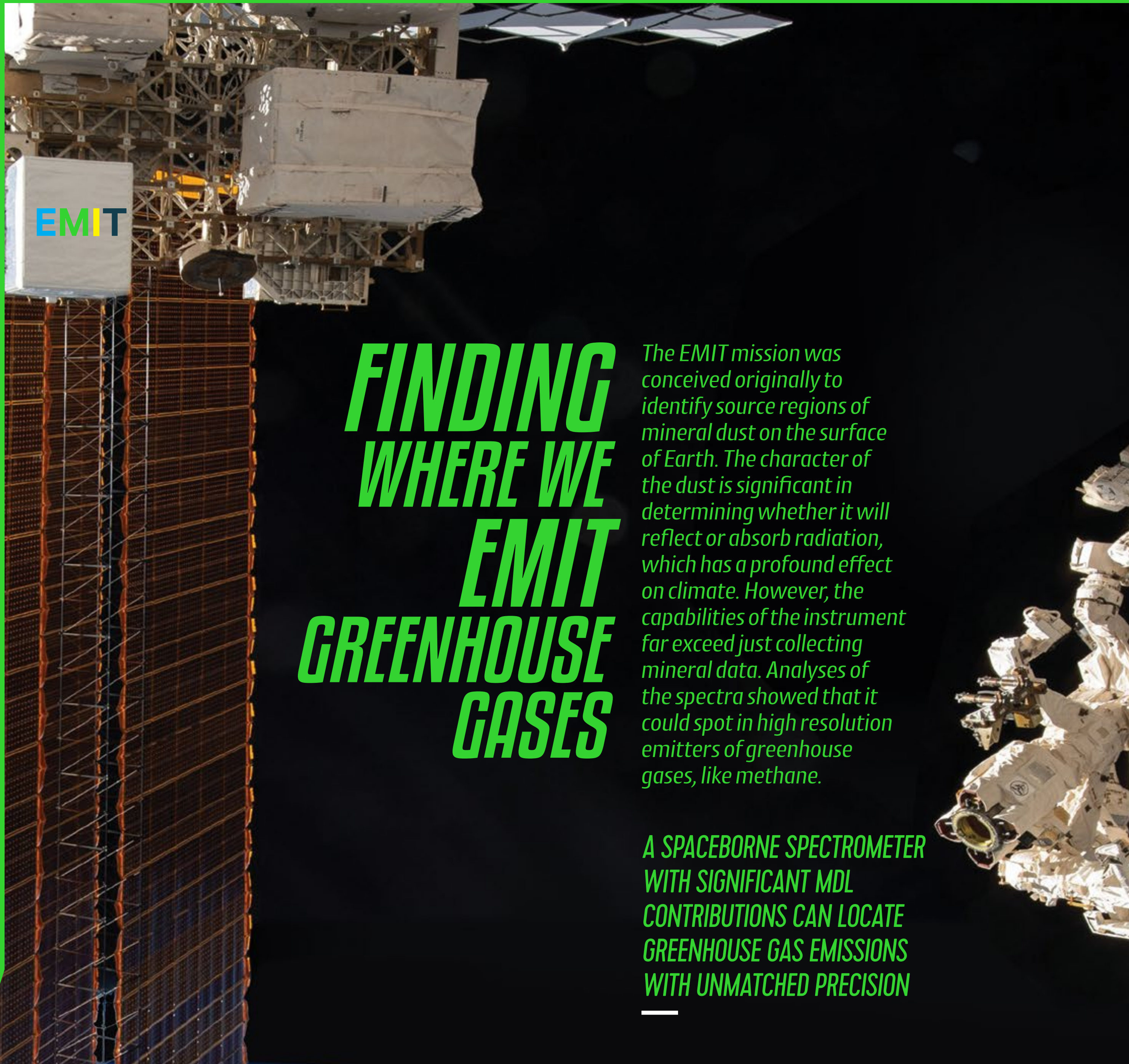
*To highlight these areas, this Annual Report is organized into four main sections. The first three align with the JPL Plan's goals: **SUCCEED**, **SEED** and **LEAD**. The fourth section addresses **MDL TECHNOLOGY PROGRESS**.*

SUCCEED
A FOUNDATION OF EXCELLENCE



MDL'S ENGINEERS AND SCIENTISTS EXCEL

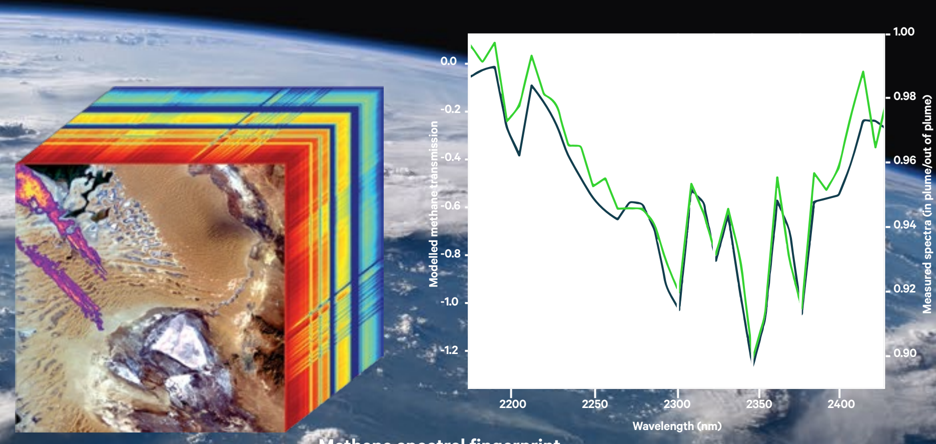
MDL staff make contributions that directly enable missions and provide new technical developments that may enable future missions. Therefore, this section comprises two parts that correspond to these contributions: major missions with MDL inputs and technical advances to support missions.



FINDING WHERE WE EMIT GREENHOUSE GASES

The EMIT mission was conceived originally to identify source regions of mineral dust on the surface of Earth. The character of the dust is significant in determining whether it will reflect or absorb radiation, which has a profound effect on climate. However, the capabilities of the instrument far exceed just collecting mineral data. Analyses of the spectra showed that it could spot in high resolution emitters of greenhouse gases, like methane.

A SPACEBORNE SPECTROMETER WITH SIGNIFICANT MDL CONTRIBUTIONS CAN LOCATE GREENHOUSE GAS EMISSIONS WITH UNMATCHED PRECISION



Methane spectral fingerprint

Greenhouse gases are a major contributor to climate change, and the two most prominent are carbon dioxide and methane. Identifying point sources of these gases is an important first step in reducing the effects of greenhouse gases on global warming. The Earth Surface Mineral Dust Source Investigation (EMIT) is a critical new tool in the fight.

The EMIT Open Data Portal shows high-confidence research grade methane plumes from point source emitters — updated as they are identified — in keeping with MDL's Open Science and Open Data policy. This mapping effort is a prototype component of the NASA Earth Science contribution to a U.S. Government Greenhouse Gas (GHG) information system.

EMIT includes the latest in imaging spectrometers. Its technological predecessors have been used for decades in airborne experiments that demonstrated the effectiveness of remote sensing to identify point sources of greenhouse gas emissions. Unlike its predecessors, however, EMIT is a spaceborne device, giving it the ability to more easily and more quickly generate global-scale datasets.

EMIT was launched to the International Space Station (ISS) on July 14, 2022. It includes an advanced two-mirror telescope and a high-optical-throughput F/1.8 Dyson imaging spectrometer mounted to the ISS exterior. The spectrometer's concave diffraction grating has a structured blaze that was written using MDL's e-beam lithography capabilities. EMIT can measure from the visible to the short-wave IR (SWIR) portions of the electromagnetic spectrum (380-2500 nm), which includes the region where both carbon dioxide and methane have their spectral fingerprints (1900-2500 nm). It can analyze sections of Earth that are 50 miles wide while still resolving the data in areas about the size of a soccer field. EMIT's ability to analyze broad swaths of territory while maintaining high resolution means it will provide the most detailed global data available on point sources of greenhouse gas emissions.

EMIT FINDINGS HELP ADDRESS CLIMATE CHANGE

EMIT Rapidly Produced Results

When EMIT returned its first data in September 2022, it identified more than 100 "super-emitters" of methane worldwide and found methane plumes that were as much as 20 miles long. The initial data showed methane emissions in New Mexico, Turkmenistan, and Iran, among many other places, and revealed methane plumes in unexpected locations where nobody would previously have thought to look. Since then, plume complexes have been found on every continent except Antarctica, and more than 300 have been identified globally. This methane data in particular is useful because methane is a much more potent greenhouse gas than carbon dioxide, but it persists in the atmosphere for only about 20 years, whereas carbon dioxide can linger for centuries. As a result, although reducing both methane and carbon dioxide emissions is important, this focus on reducing methane emissions could be a more effective way to fight climate change in the short term.

In addition to location, EMIT data can also be used to estimate how quickly greenhouse gases are flowing. This combined information on both the rate and place of greenhouse gas emissions can therefore provide insight into the effectiveness of cleanups and leak repairs or help with efforts to recapture greenhouse gases.

CONTINUING MDL'S LONG, SUCCESSFUL DEVELOPMENT OF DIFFRACTION GRATINGS AND SLITS

All the data generated by EMIT have been and will be made publicly available, further supporting worldwide efforts to reduce greenhouse gas emissions.

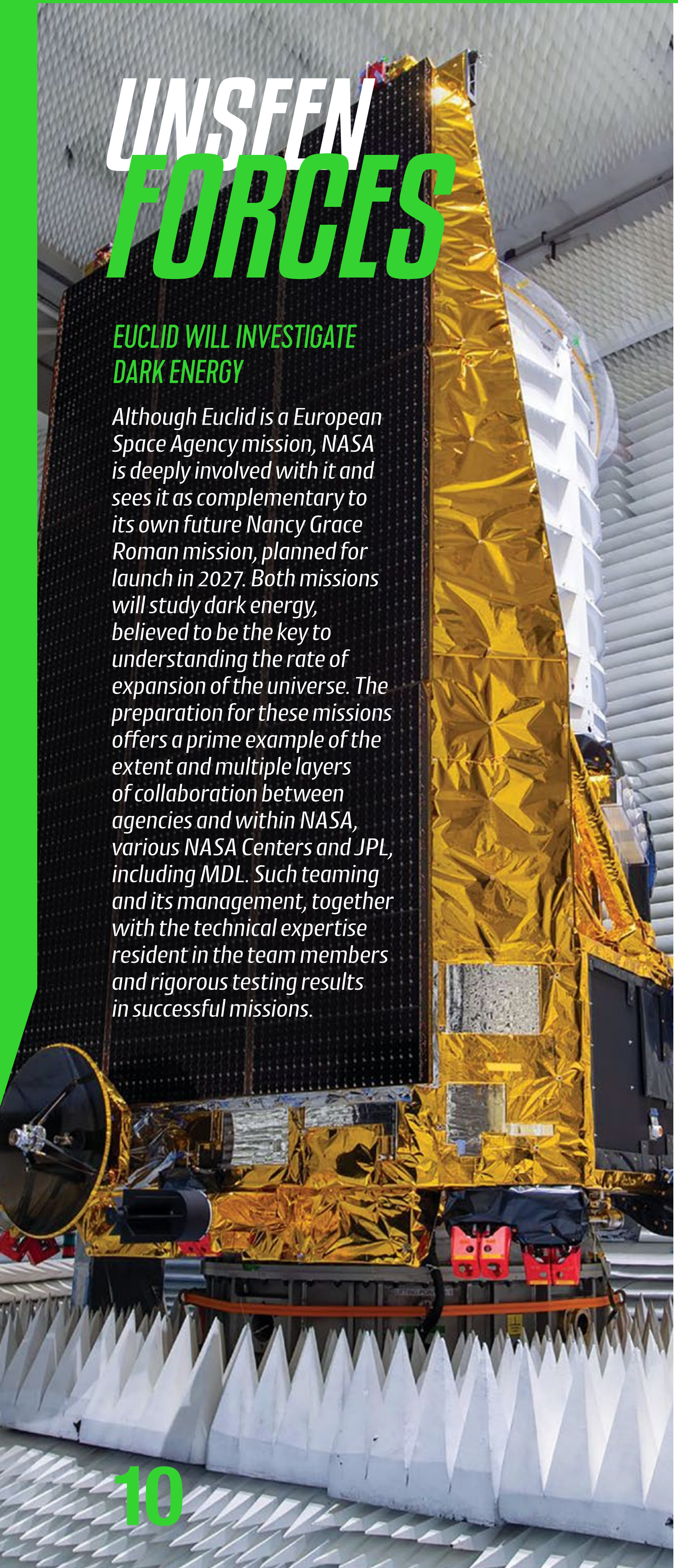
During EMIT's initial one-year mission, it is expected to collect over 1 billion usable measurements. Barely halfway into that mission, EMIT has already exceeded all expectations and has provided a wealth of data to aid in the fight against climate change. The UN, the US State Department, the Environmental Protection Agency, state agencies, philanthropic organizations, the press, and many others have invested in Earth's future by using EMIT's observations to support current greenhouse gas mitigation efforts.

EMIT SUCCEED

UNSEEN FORCES

EUCLID WILL INVESTIGATE DARK ENERGY

Although Euclid is a European Space Agency mission, NASA is deeply involved with it and sees it as complementary to its own future Nancy Grace Roman mission, planned for launch in 2027. Both missions will study dark energy, believed to be the key to understanding the rate of expansion of the universe. The preparation for these missions offers a prime example of the extent and multiple layers of collaboration between agencies and within NASA, various NASA Centers and JPL, including MDL. Such teaming and its management, together with the technical expertise resident in the team members and rigorous testing results in successful missions.



EUCLID

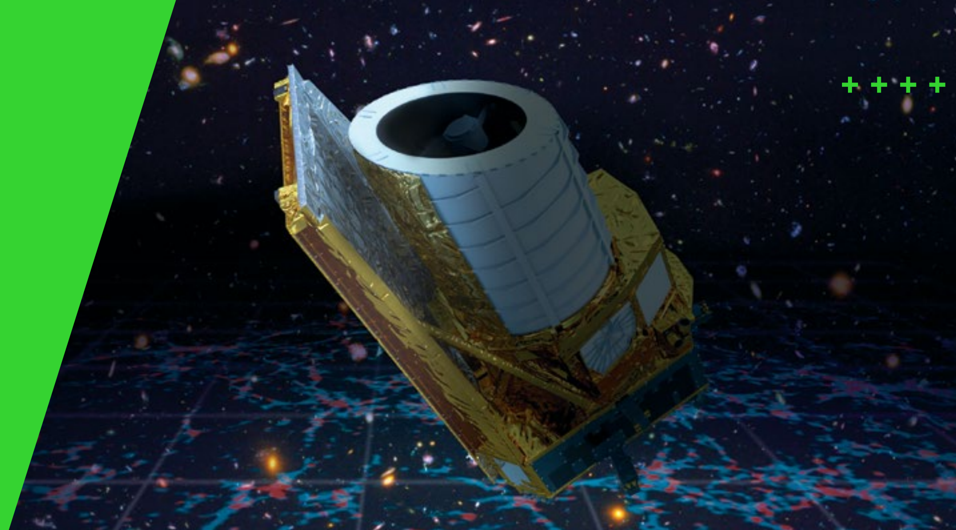
The expansion of the universe is accelerating, but there is still not a clear understanding of why. Dark energy contributes to this expansion. It, in turn, is influenced by dark matter, which makes up 80% of the matter in the universe.

To better understand the nature of dark energy and dark matter, the European Space Agency (ESA) Euclid spacecraft, launched in July 2023, will create a 3D map of one-third of the sky, including millions of galaxies, as well as dark matter itself. The data generated from looking at distant galaxies as they were approximately 3 billion years ago and comparing them with closer galaxies whose light was emitted more recently will help understand how dark matter and dark energy affect galactic behavior.

Euclid launched with two main instruments on board: a visible-light imager (VIS) and a near-infrared spectrophotometer (NISP). In 2019, JPL delivered 16 sensor chip systems that included IR detectors, cables, and cryogenic electronics for use in the spacecraft. JPL's MDL provided a key contribution to EUCLID, and the functioning of its application-specific integrated circuit (ASIC) package — an MDL manufactured flight silicon fan-out board connection design previously developed, fabricated, and delivered for the Herschel Space Observatory and Planck ESA missions.

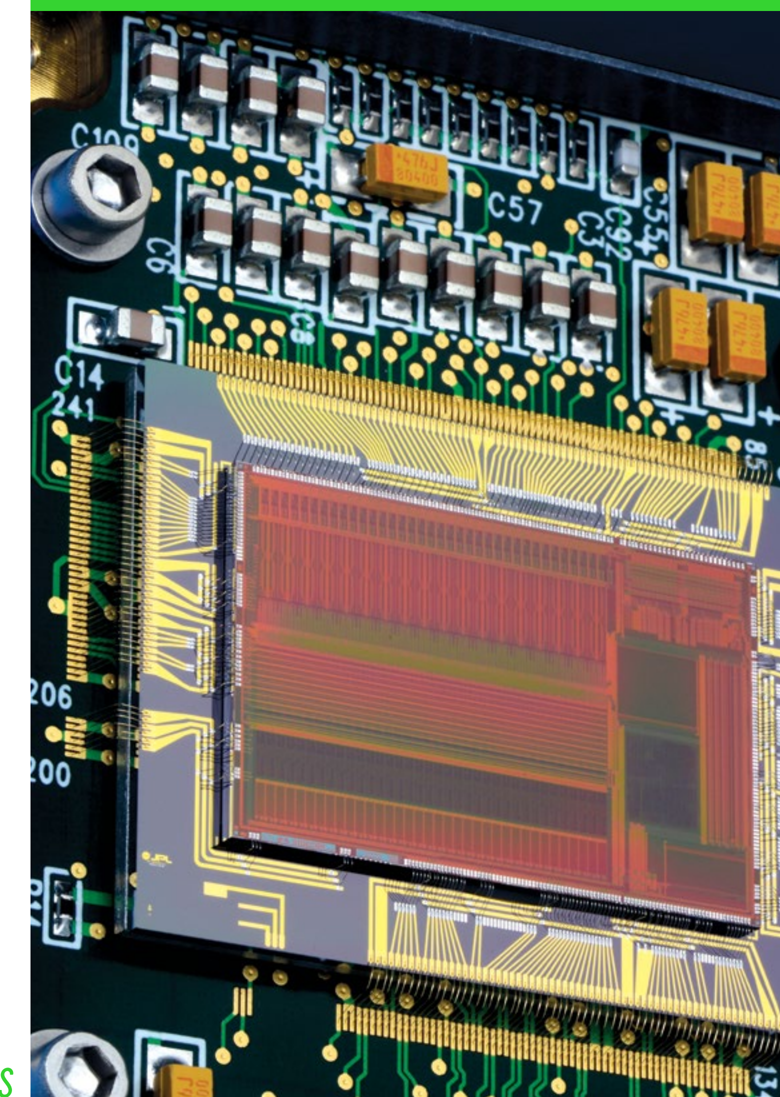
Euclid's sunshield and solar panel protect the telescope from nearby IR sources like the Sun, Earth, and the Moon. (Credit: ESA/M.Pédoussaut)

MDL MANUFACTURED COMPONENTS FOR THE APPLICATION-SPECIFIC INTEGRATED CIRCUIT PACKAGE



The silicon fan-out interfaces the fine wire bond pitch on the ASIC with a wider wire bond pitch on printed circuit boards. This fan-out connection design eliminated a problem with an initial design for EUCLID that was seeing the breaking of wire bonds to the ASIC chip during thermal cycling to low cryogenic temperatures below 130K.

The processes and technologies developed for Euclid will have direct effects on several future missions, including those to the moons of outer planets. They can also be used on Earth in superconducting quantum computing. Most notably, the Nancy Grace Roman Space Telescope, scheduled for launch in 2027, will build on Euclid's advances. The Roman Telescope will study a smaller part of the sky but will do so in more detail, providing a complementary data set to Euclid's. Together, the two missions will foster a clearer understanding of dark matter, dark energy, and how they work together to shape the universe.



JPL LED THE PROCUREMENT AND DELIVERY OF THE DETECTORS FOR EUCLID'S NEAR INFRARED SPECTROMETER AND PHOTOMETER INSTRUMENT. THE DETECTORS AND SENSOR CHIP ELECTRONICS WERE TESTED AT NASA'S DETECTOR CHARACTERIZATION LAB AT THE GODDARD SPACE FLIGHT CENTER.

Cryogenic electronics packaging for Euclid

SUCCEED

MDL SIGNIFICANTLY CONTRIBUTES TO LANDMARK MISSIONS

MDL's products are key components of instruments that allow mission concepts to be conceived and launched.

This part highlights recent MDL-facilitated missions that have made headlines. The data they have generated are already fundamentally changing our understanding of our planet and our universe.

Fiery Hourglass

Exoplanet Atmosphere

Early Galaxies

Pillars of Creation

JWST THE UNIVERSE IN FOCUS

A 30 YEAR TRACK OF MDL FLIGHT COMPONENT DEVELOPMENT CULMINATING IN AN OUTSTANDING MISSION

The James Webb Space Telescope is revealing more about the universe that we ever imagined

The James Webb Space Telescope (JWST) was launched at the end of 2021, the culmination of approximately 30 years of development. Planning for JWST began with identifying the need for a successor to the Hubble Space Telescope (HST), as outlined in the 2000 Decadal Survey "Astronomy and Astrophysics in the New Millennium." The survey identified the need for a greater spectral range, including into the IR; an order of magnitude better image sharpness; and two orders of magnitude greater sensitivity. The HST successor was initially called the Next Generation Space Telescope (NGST) and was given the highest priority in the survey; it was renamed in 2002 to honor NASA's second administrator.

MDL is not unused to working on a 30-year period spanning the invention of a new technology or component through various development phases until it is selected for a mission, followed by years of preparation for launch after the mission itself has been selected. In this case, the mission is a true milestone. JWST is only about half the mass of the HST and has a 6.5-meter (21-foot)-diameter gold-coated beryllium primary mirror made of 18 separate hexagonal mirrors. Despite its smaller mass, the results from its first months of operation have yielded an immense range of scientific insights, from seeing the birth of a new star, looking back in time to near the beginning of the universe, and seeing some of the first galaxies to ever form. The JWST Near Infrared Camera (NIRCam) coronagraph, made possible by five MDL-fabricated flight occulting masks, has even enabled the imaging of an exoplanet and the characterization of its atmosphere. NIRCam has not only enabled new science returns, but it also aided in the alignment and verification of the JWST mirror deployment.

MDL FABRICATED FIVE FLIGHT-OCCULTING MASKS FOR THE NEAR INFRARED CAMERA CORONAGRAPH

EARLY SCIENCE DATA RETURNS FROM THE JWST INSTRUMENTATION ARE EXPANDING OUR KNOWLEDGE AND UNDERSTANDING OF THE UNIVERSE

Fiery Hourglass as a New Star Forms

The blazing clouds within the Taurus star-forming region are only visible in IR light, making them an ideal target for JWST's NIRCam. They conceal a protostar, L1527, which is hidden within the "neck" of the hourglass shape. An edge-on protoplanetary disc is seen as a dark line across the middle of the neck. Light from the protostar leaks above and below the disc, illuminating cavities within the surrounding gas and dust. JWST also reveals filaments of molecular hydrogen that have been shocked as the protostar ejects material. Shocks and turbulence inhibit the formation of new stars, which would otherwise form throughout the cloud. As a result, the protostar dominates, taking much of the material for itself.

Despite the chaos that L1527 is causing, it is only about 100,000 years old — a relatively young body. Given its age and its brightness in far-IR light as observed by missions like the Infrared Astronomical Satellite, L1527 is considered a class 0 protostar, the earliest stage of star formation. It does not yet generate its own energy through the nuclear fusion of hydrogen, an essential characteristic of stars. Its shape, while mostly spherical, is also unstable: it is a small, hot, and puffy clump of gas somewhere between 20% and 40% of the mass of our Sun.

The surrounding molecular cloud is made up of dense dust and gas that are being drawn towards the center, where the protostar resides. As the material falls in, it spirals around the center, creating a dense accretion disc that feeds material into the protostar. As the protostar gains more mass and compresses further, the temperature of its core will rise, eventually reaching the threshold for nuclear fusion to begin.

The accretion disc, seen in the image as the dark band in front of the bright center, is about the size of our solar system. Given the density, it is not unusual for much of this material to clump together — the beginnings of planets. Ultimately, this view of L1527 provides a window into what our Sun and solar system looked like in their infancy. /

Exoplanetary Atmospheres

JWST has revealed new information about WASP-39b, a "hot Saturn" (a planet about as massive as Saturn but in an orbit tighter than Mercury) orbiting a star approximately 700 light-years away. While JWST and other space telescopes, including the HST, have previously revealed isolated ingredients of this heated planet's atmosphere, new readings provide a full accounting of atoms, molecules, and even signs of active chemistry and clouds. Water, sulfur dioxide, carbon monoxide, sodium, and potassium have all been identified, exciting the exoplanet science community. The latest data also give a hint of how these clouds might look up close: broken up, rather than as a single, uniform blanket over the planet.

These findings bode well for the capability of JWST's instruments to conduct a broad range of investigations of exoplanets, including probing the atmospheres of smaller, rocky planets like those in the TRAPPIST-1 system. For the first time, we have seen concrete evidence of photochemistry — chemical reactions initiated by energetic stellar light — on exoplanets. This observation is relevant to potential signs of habitability in the future. /

The Universe's Early Galaxies

A few days after officially starting science operations, JWST enabled astronomers to peer into a realm of early galaxies beyond the reach of all previous telescopes. JWST is now unveiling a very rich universe where galaxies as they first formed look remarkably different from the mature galaxies seen today. Researchers have found two exceptionally bright galaxies that existed approximately 300 and 400 million years after the Big Bang, with redshifts of approximately z = 12.5 and 10.5, respectively. Their extreme brightness is puzzling. These young galaxies are transforming gas into stars very rapidly, and they appear compacted into spherical or disc shapes that are much smaller than our Milky Way. The onset of stellar birth in these galaxies may have been just 100 million years after the Big Bang, which happened 13.8 billion years ago. Future spectroscopic measurements with JWST will help confirm these hypotheses. /

Dust and Structure in the Pillars of Creation

The giant Pillars of Creation, shown on the opposite page, are formed from the gas and dust that surround the stars forming there. They gleam at their edges, hinting at the stellar activity within. The HST produced the first images of them in 1995. Since then, different wavelengths of light and new instruments have increasingly improved models of how stars form.

The JSWT has now captured images of the pillars in mid-IR light, which details where dust is but not the stars themselves. The areas of densest dust are the darkest shades of gray. The red V-shaped region toward the top shows diffuse, cooler dust. The densest part of the Milky Way's disc contains too much gas and dust and hides background galaxies.

JWST's near-IR NIRCam images indicate that many thousands of stars formed here. However, with the Mid-Infrared Instrument (MIRI), which can see dust, most stars are missing because newly formed stars have no dust around them. MIRI can only see young stars still surrounded by sufficient dust. These stars are the crimson orbs toward the edges of the pillars. In contrast, the blue stars are aging, having shed most of their layers of gas and dust. /

SUCCEED

MDL'S DEVELOPMENTS SUPPORT NASA MISSIONS

The Curiosity Mars rover used its navigation cameras to capture panoramas of Marker Band Valley

MDL TECHNOLOGY ADVANCEMENTS LIE AT THE HEART OF ITS PRODUCTS

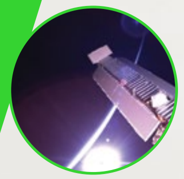
These technology advancements are at varying stages of maturity; some are entirely new, and others are adaptations of prior technologies for use in new applications. They have a wide range of uses: for example, some will help ensure astronaut safety in space, while others will facilitate communication from farther distances than ever before. What unifies them all is their ability to push the boundaries of space exploration.

JPL has long been known for producing remarkable cameras that have enabled landmark missions, including the Japanese Yohkoh mission in 1991, the camera that allowed the repair of the Hubble Space Telescope in 1992, Cassini in 1997, the Mars Exploration Rovers in 2003, and the Mars 2020 Perseverance Rover. MDL technology has been at the heart of each of these cameras. That technology, in turn, could only be developed through collaboration within JPL that involved MDL and many other units.

PRICELESS PHOTOS

ENHANCED ENGINEERING CAMERAS PROVIDE A COMPELLING VISUAL RECORD OF CURRENT AND FUTURE MARS MISSIONS

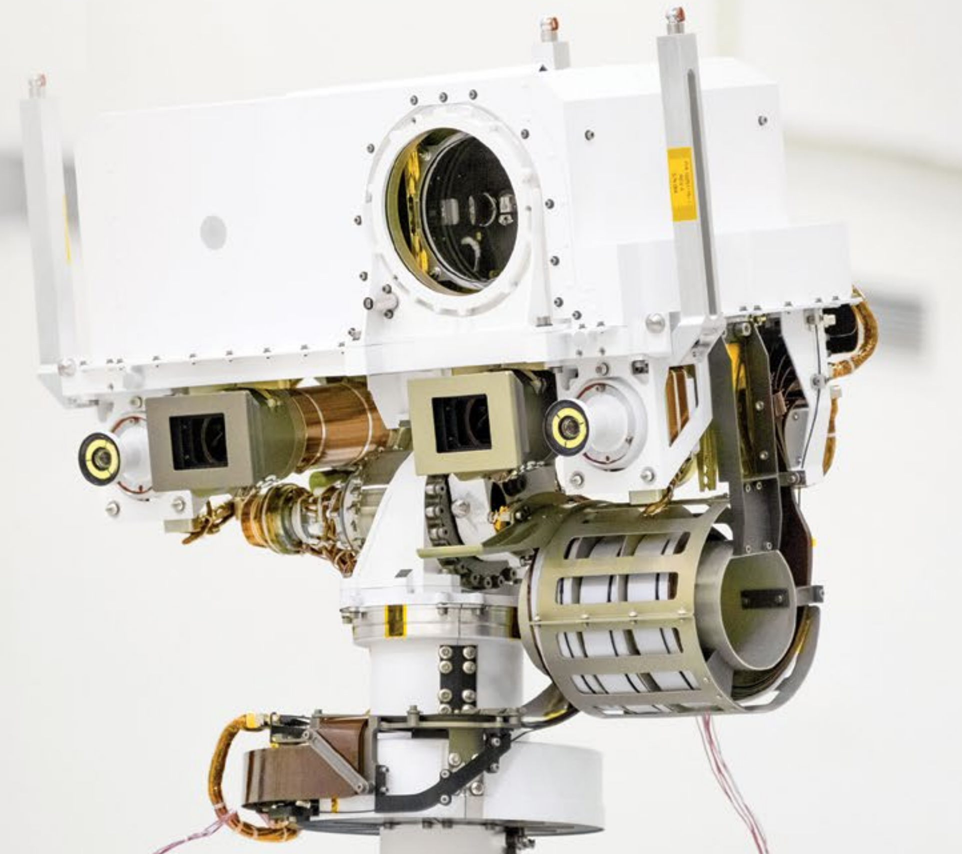
Some of the most striking information received from the Mars rovers has come from photographs. On the Perseverance rover, many of these photos were collected by its enhanced engineering cameras (EECAMs). Building on that success, the Mars Sample Return Lander (SRL), currently in development, is planned to carry six more of these cameras to Mars. These new EECAMs would be functionally identical to their predecessors but would fulfill a very different mission with new objectives: to return Martian rock samples to Earth for analysis.

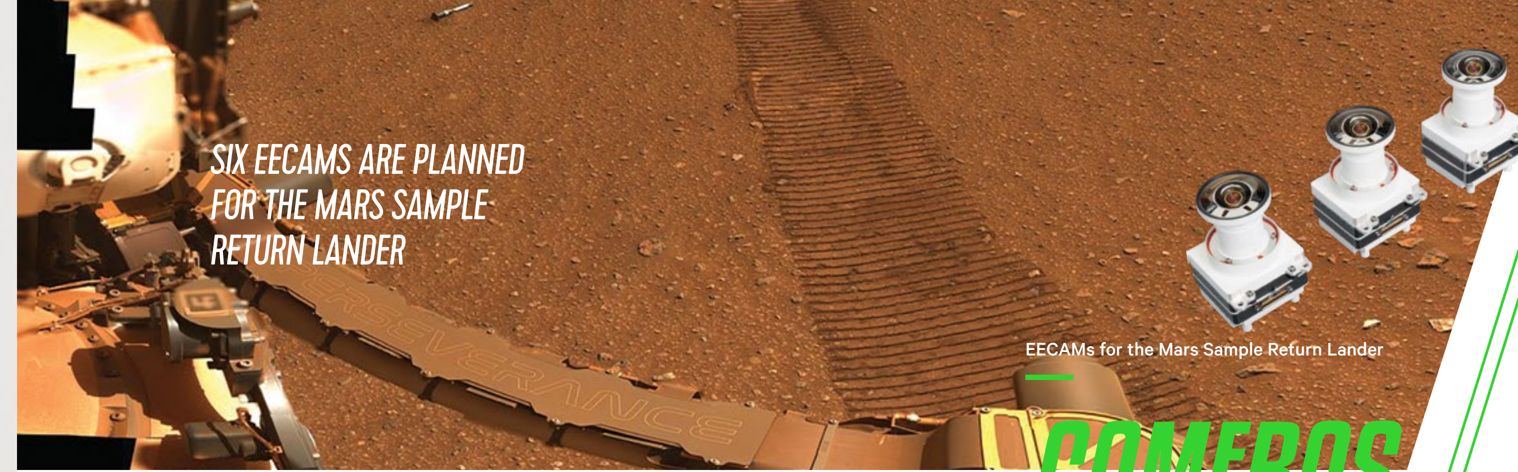
M20202 landing (left) and SWOT deployment (right) filmed with ruggedized COTS cameras


Context camera for the Ocean Carbon Observatory (OCO-3) launched in 2019 to the ISS

MDL modifies and qualifies COTS hardware for space applications



THE PERSEVERANCE ROVER CONTAINS SEVERAL EECAMs



SIX EECAMS ARE PLANNED FOR THE MARS SAMPLE RETURN LANDER

EECAMs for the Mars Sample Return Lander

CAMERAS

On the SRL, four EECAMs would be attached to the outside of the lander and function as two redundant pairs capable of stereoscopic terrain reconstruction. Both pairs would be located on the same side of the lander, close to the sample transfer arm. One pair would be above and one pair would be below the access door to the bay, which would contain the orbiting sample system where sample tubes would be transferred from Perseverance to a basketball-sized container for their trip to Earth. The lander would also harbor helicopters, so the EECAMs would map the ground in front of the lander to allow safe operation of the helicopters when landing and driving to and from their landing pads. The cameras would also allow the observation of the other critical imaging zones where the sample tubes would be transferred from Perseverance to the lander arm for storage in the return vehicle and at the rover parking location. The remaining two EECAMs would be inside the orbiting sample (OS) bay, both aimed at the tube container to observe the tubes being loaded before sealing them for their journey.

The EECAMs used for the SRL would be a rebuild of the Mars 2020 cameras, using the same 20-megapixel complementary metal–oxide–semiconductor (CMOS) detectors for high-resolution color images and the same lens that was used for the Mars 2020 hazard avoidance cameras (HazCams). The cameras' resolution and wide field of view allow for the detection of fine terrain features over the whole operation range and are critical to stereo image reconstruction.

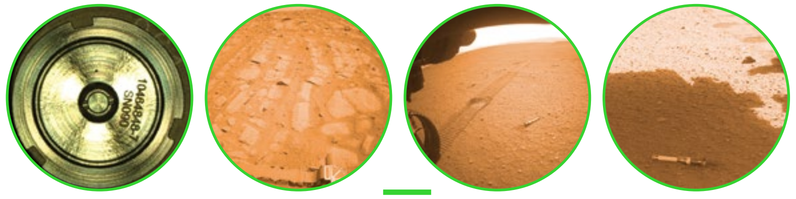
An important aspect of camera development is the use of commercial off-the-shelf (COTS) components. The landing of the Perseverance rover on Mars was filmed thanks to a collection of COTS USB cameras connected to a storage unit made of additional COTS hardware, including a single-board computer, a solid-state drive, and a custom circuit board to interface with the rover's communication system to retrieve the images. A modified version of this imaging system was flown on the Surface Water and Ocean Topography (SWOT) mission launched in December 2022. The goal for the imaging system was to observe the deployment of the solar panels and the complex multi-step opening of the deployable antenna, and it yielded fabulous images of these critical steps at the beginning of the SWOT mission.

Launching COTS hardware allows the addition of telemetry to a vehicle for a lower cost than a fully qualified or a custom-designed system.

Some care was taken to ruggedize the components, such as opening the cameras to stake the larger electronics components and replacing or removing parts made of either unknown materials or materials with high outgassing or contamination.

Another camera very similar to the Mars-bound EECAM, built around the same high-resolution CMOS detector, is the Orbiting Carbon Observatory (OCO)-3 class C/D context camera, which has been flying aboard the International Space Station (ISS) since 2019 and demonstrates the adaptability of the architecture to other mission classes. Built with stackable connectors and ruggedized commercial lenses, it still carried the flight screening and heritage of the electronic parts and a mechanically solid design. Its younger sibling, the NEAScout navigation and science camera, delivered to the Marshall Space Flight Center in 2017, holds the same electronics and a similar rugged commercial lens but was assembled on a lighter chassis for a lower-mass version meant for inside the enclosure of a CubeSat.

M2020 EECAMs for SRL



M2020 EECAM high-resolution camera mission images

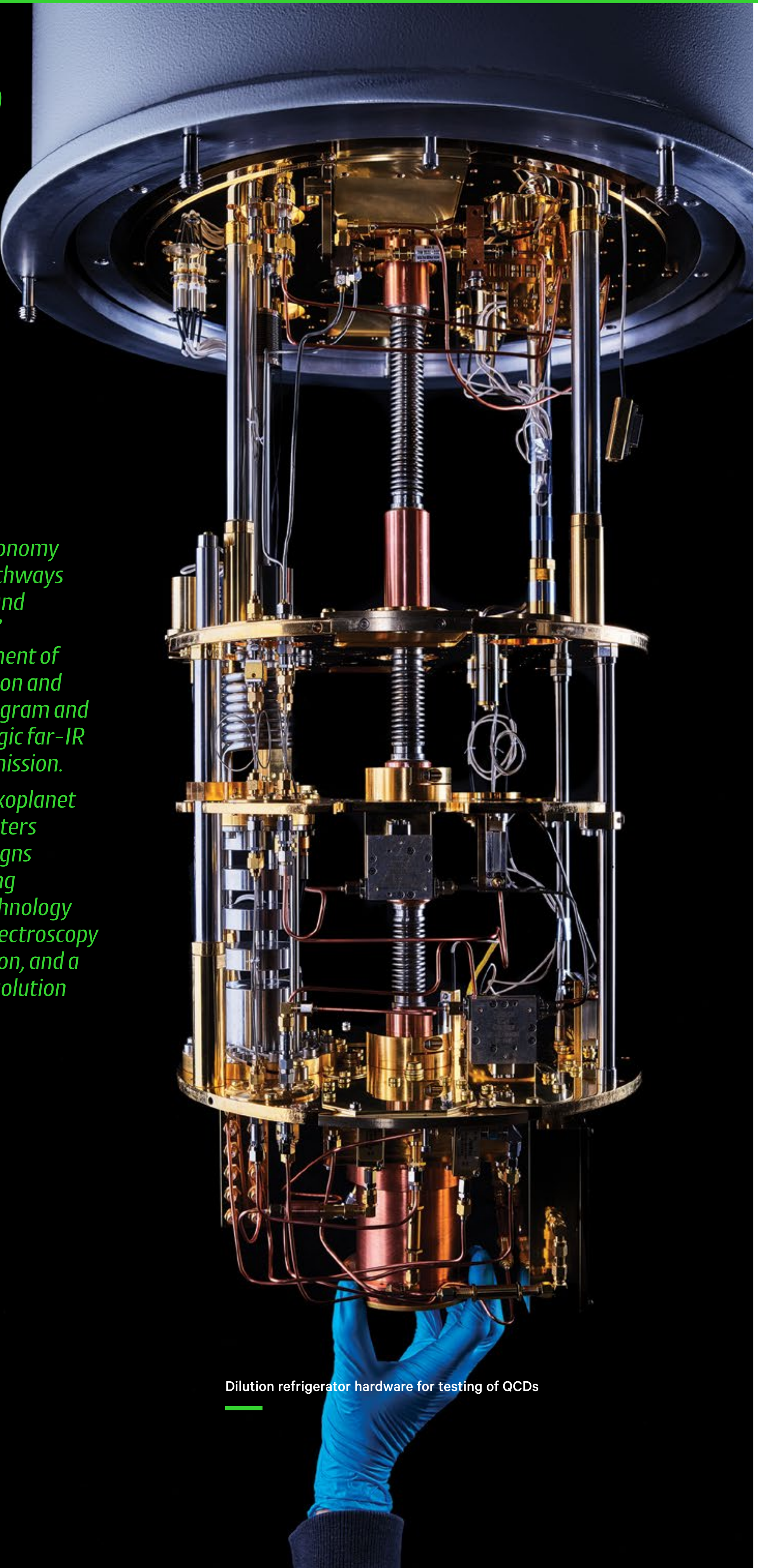
SUCCEED

SEEING INTO THE DARK

The Decadal Survey on Astronomy and Astrophysics 2020, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," recommends the establishment of a Great Observatories Mission and Technology Maturation Program and specifically calls for a strategic far-IR spectroscopy and imaging mission.

After an IR/optical (O)/UV exoplanet and astrophysics mission enters formulation, the survey assigns equal priority to commencing mission maturation and technology development for a far-IR spectroscopy and imaging strategic mission, and a high spatial and spectral resolution X-ray strategic mission.

QUANTUM CAPACITANCE DETECTORS WILL ENABLE A NEW GENERATION OF TELESCOPES



Dilution refrigerator hardware for testing of QCDs

QCDs

Any major future orbital astronomical facilities, such as the Surveyor-class Origins Space Telescope (OST), will require large arrays of mid- and far-IR detectors, which will help "see" through cosmic dust and detect light from the most distant galaxies. The OST will require $5x10^4$ detectors spanning wavelengths continuously from 10 µm to 400 µm, with noise equivalent powers (NEPs) of $4x10^{-20}$ W $Hz^{-1/2}$ for the most demanding instrument module. Fortunately, such NEP requirements have already been exceeded by a new class of superconducting detectors called quantum capacitance detectors (QCDs). QCDs have demonstrated NEPs as low as $2x10^{-20}W/Hz^{1/2}$ and can detect and count single 1.5 THz photons in both single-pixel and large-array (441 pixel) formats.

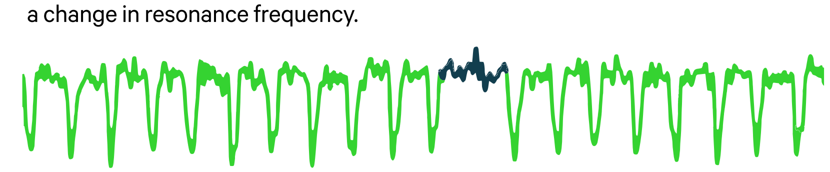
However, to satisfy all the requirements of future observatories like the OST, QCDs have to be developed further to demonstrate a tenfold larger dynamic range than that of current prototypes, as well as larger array ($5x10^4$) formats.The QCD is based on the single Cooper-pair box, a device initially developed as a qubit. In a QCD, an island of superconducting material is connected to a superconducting absorber via a small tunnel junction and biased by a gate capacitor with a linear periodic voltage ramp in a sawtooth format. The capacitance of the island displays a periodic stream of peaks as a function of the gate voltage; this trait is called the quantum capacitance. The device is embedded in a resonator, and a change in capacitance is detected via a change in resonance frequency.

A photon striking the absorber breaks the Cooper pairs, creating a population of quasiparticles that tunnel into the island with a high rate. This tunneling prevents the formation of a quantum capacitance peak, introducing a gap in an otherwise periodic stream of peaks. This gap represents the detection of a single photon.

In a major milestone in 2022, single 1.5 THz photons were counted with a 21x21 pixel array. This development is a major stepping stone for a future 50,000-detector array.

From concept formulation to prototype fabrication and characterization at mK temperatures, QCDs were developed entirely at MDL. Their development required a large variety of MDL equipment, such as the EX3 stepper, maskless aligner, e-beam lithography system, superconducting material deposition systems and a cryogen-free dilution refrigerator for characterization.

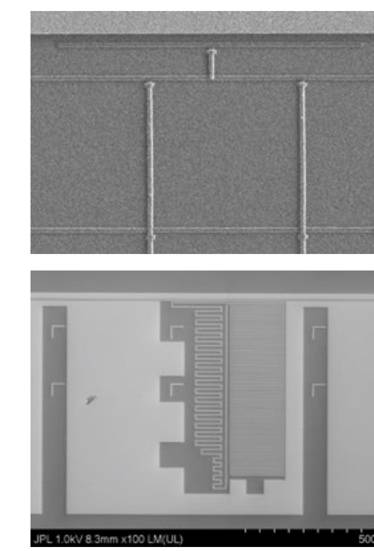
Future work on the QCD will concentrate on scaling up to arrays of 50,000 pixels, increasing the dynamic range and reducing the dark counts. Its major application will be a future spaceborne, cryogenic far-IR telescope such as the OST. Another promising area of application is in the detection of dark matter and dark radiation, which could interact with an interface between materials with different dielectric constants, generating electromagnetic radiation in the far-IR.



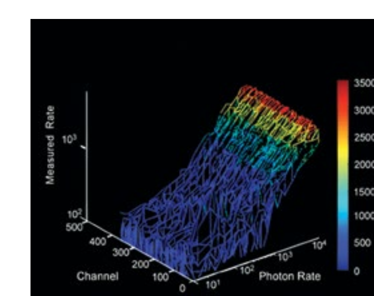
Quantum capacitance signal displaying a missing dip highlighted in black due to the absorption of a single far-IR photon

21x21 array of QCDs

DETECTION IN THE FAR-IR WILL HELP SEE THROUGH DUST CLOUDS IN SPACE



Micrograph of a QCD pixel



Measured photon rate as a function of expected photon arrival rate for the 21x21 array of QCDs

SUCCEED

DISTANT EARLY WARNING

HYTI, A 6U CUBESAT DEMONSTRATION WILL HELP BETTER PREDICT VOLCANIC ERUPTIONS, DETECT WILDLAND FIRES, AND MONITOR SOIL MOISTURE ON THE GROUND

Humanity is constantly faced with human-made and natural challenges. Being able to predict and respond quickly to both will be essential for successful, sustainable living in the future

MDL is developing technologies for NASA to meet these future challenges. For example, climate change is making water an increasingly scarce resource, and the world's 1,500 active volcanoes threaten many people, especially the ~800 million who live within 100 km of one of them. Therefore, the ability to monitor soil moisture and accurately predict volcanic eruptions could save thousands of lives in both the short and long term.

Another example of where it could have been of use was the Dixie Fire, an enormous wildfire that burned in California in 2021. It burned nearly one million acres before being 100% contained after 4 months. It was the largest single wildfire in recorded US history, and the second-largest wildfire overall. This fire completely destroyed several small towns, burning an area larger than the state of Rhode Island.

Smoke from the Dixie Fire polluted Earth's atmosphere across the Western United States, including states as far east as Utah and Colorado, with unhealthy air quality. The Dixie Fire was the most expensive wildfire fought in the US history costing ~$640 million to suppress.

AN MDL-DEVELOPED HOT-BIRD FPA TECHNOLOGY WILL PROVIDE HIGH RESOLUTION AND SENSITIVITY AT HIGH TEMPERATURES WHILE CONTROLLING COSTS

A HOT-BIRD sensor and its electronic support system

HOT-BIRD

Long-wave IR (LWIR) radiation can provide valuable information about soil moisture on the ground to estimate the wildland fuel loads and volcanic gases in the atmosphere, but LWIR data with high spatial and temporal resolution has not yet been achieved from space. The Hyperspectral Thermal Imager (HyTI), a 6U CubeSat technology demonstration, is set to change that. A collaboration between the Hawai'i Institute of Geophysics and Planetology at the University of Hawai'i Manoa, The Hawai'i Spaceflight Laboratory, JPL, and Saraniasat, Inc., HyTI is scheduled for launch in the early part of 2024 and will demonstrate high spatial, temporal, and spectral resolution imaging from space by using several key innovations.

The key enabling technology behind the HyTI smallsat demonstration is the high-operating-temperature quantum structure-based barrier infrared detector (HOT-BIRD) focal plane array (FPA) technology developed at MDL. The HOT operation of the BIRD FPA will support detection while conserving the satellite's limited onboard power. The salient features of the III-V compound semiconductor quantum structure based BIRD FPAs are lower dark current, high quantum efficiency, and extremely low 1/f noise. The extremely low 1/f noise completely eliminated the necessity of a frequent on-board calibration process, while the low dark current and high quantum efficiency increased the signal-to-noise ratio of the HyTI instrument.

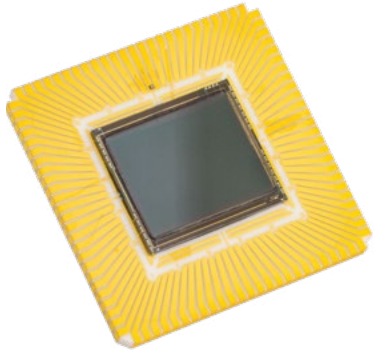
Finally, the implementation of HOT FPA operation and the elimination of the on-board calibrator helped to reduce the HyTI instrument size to 2U including the COTS optics package. In addition, high-performance onboard computing will allow data processing on board the satellite itself, yielding analysis-ready data for scientists to download and study.

Given that ~3 petabytes of data are expected to be generated per year, this on-board processing capability will streamline analysis for the scientists on the mission team.

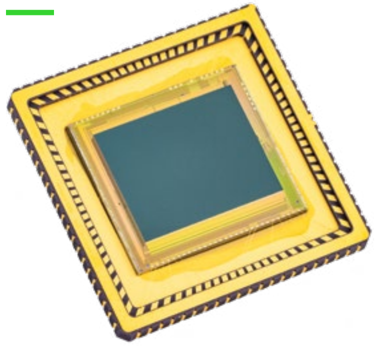
From its orbit at 430 km above Earth, HyTI will have 60-m ground resolution and 25 bands of spectral resolution in the 8.0-10.7-μm range, with narrow-band noise equivalent variation in temperature (NEdT) of less than 150 mK and a peak signal-to-noise ratio of ~500:1. This advanced spatial and spectral resolution will allow the quantification of volcanic sulfur dioxide in the atmosphere and the radiation of heat from the ground. These insights will help support better management of cropland and better prediction and preparedness for volcanic activity.

Eventually, a constellation of 25-30 HyTI satellites could orbit Earth and monitor soil moisture, wildland fires and volcanic eruptions more accurately and cheaply than a single conventional satellite could. Such a low-cost smallsat constellation could provide continuous monitoring of Earth's atmosphere, delineating human-made and natural challenges, and would provide the ability to respond quickly which is essential for successful, sustainable living in the future and help humanity prepare for both immediate and long-term threats to our safety and security. Thus, HyTI fits seamlessly into NASA's mission to innovate for the benefit of humanity.

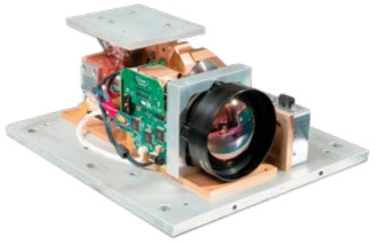
HyTI is funded by NASA's Earth Science Technology Office (ESTO) InVEST (In-Space Validation of Earth Science Technologies) program managed by Sachidananda Babu. The HyTI instrument was developed at JPL, and the HyTI smallsat was developed at the University of Hawaii.



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



The same sensor in a leadless chip carrier for testing



HyTI instrument on instrument test bed

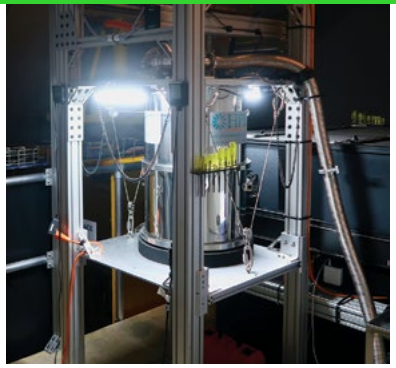
Eventually, a constellation of HyTI satellites could provide continuous monitoring of Earth's atmosphere, delineating human-made and natural challenges, and would provide the ability to respond quickly which is essential for successful, sustainable living in the future and help humanity prepare for both immediate and long-term threats to our safety and security. Thus, HyTI fits seamlessly into NASA's mission to innovate for the benefit of humanity.

SUCCEED

COMMUNICATION IS KEY

Future space missions will incorporate increasingly complex instruments that capture ever-larger volumes of data, such as high-definition images and videos. Currently, NASA space missions communicate with Earth via the radio antennas of the Deep Space Network (DSN), which is rapidly approaching its bandwidth limit. Much like how optical fibers support faster data rates than do copper wires, optical communication could speed up deep-space data transfer by 10- to 100-fold versus traditional radio frequency (RF) communication for the same mass and power on a spacecraft.

SUPERCONDUCTING NANOWIRE SINGLE PHOTON DETECTORS ACHIEVE WORLD-LEADING PERFORMANCE

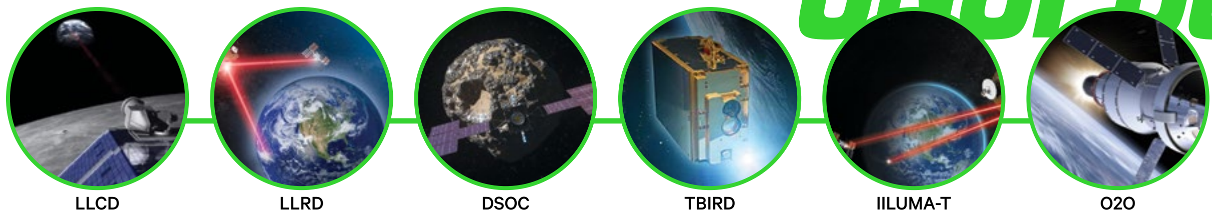


DSOC cryostat in Palomar spectrograph room

Optical communication has been demonstrated successfully as far as the Moon, and now NASA wants to extend the range to Mars-like distances and mature lunar-distance optical communication. Superconducting nanowire single-photon detectors (SNSPDs) are a key technology for deep space optical communication ground receivers. They are based on a narrow superconducting wire cooled to approximately one degree above absolute zero and biased below its critical current. The absorption of just one photon in the nanowire can cause a detectable voltage pulse with a timing precision as low as 3 picoseconds.

SNSPDs have also demonstrated detection efficiencies as high as 98% at telecom wavelengths. At Mars-like distances, the most efficient way to transmit optical data from a spacecraft is to encode the data in the arrival times of laser pulses. The laser beam diverges as it travels to Earth, and it suffers further losses in Earth's atmosphere. When the pulses are finally collected by a telescope and detector, only a handful of photons remain. SNSPDs' exceptional timing resolution and ability to detect those photons with high efficiency are therefore critical for deep-space optical communication receivers. MDL is a global leader in SNSPD development and has contributed major breakthroughs in improving detector efficiency, timing resolution, active area, array scale, dynamic range, and dark count rate; ten years ago, MDL was involved in the first project to implement optical communication at lunar distances, the Lunar Laser Communication Demonstration (LLCD).

SNSPDs SUCCEED



Timeline of current and future laser communications missions

The first project to demonstrate optical communication from extra-lunar distances will be the Deep Space Optical Communication (DSOC) technology demonstration. The DSOC project includes a high-powered ground laser transmitter, an SNSPD-based ground receiver, and a flight transceiver. The transceiver will launch in October 2023 on the Psyche mission to the asteroid 16 Psyche, in the asteroid belt. Psyche is unique: it is made of nickel and iron rather than the more-typical ice or rock. Psyche may be the exposed core of an early planet, and if so, it could provide a window into the violent history of collisions and accretion that created terrestrial planets like Earth. The mission will facilitate a better understanding of Psyche's age, composition, and origin. The spacecraft's trajectory from Earth will provide the perfect proving ground for the DSOC system to test a variety of data rates over a range of distances. The Psyche spacecraft will reach distances almost 1,000 times farther than the distance from Earth to the Moon, resulting in a significant technological challenge.

To help meet this challenge, MDL developed a 64-channel SNSPD array with a 320 mm active area that can count single photons with 100-picosecond timing resolution at rates up to 1 billion counts per second. When the array was fabricated in 2018, it had the largest active area and highest dynamic range of any SNSPD detector.

Since then, a collaboration between the National Institute of Standards and Technology (NIST) and JPL has demonstrated kilopixel-scale SNSPD arrays with millimeter-scale active areas, and groups at JPL and elsewhere have measured small arrays with higher count rates — technological advances that could enable future improvements in classical or quantum optical communication data rates. In lab tests, the DSOC ground receiver system closed links at data rates up to 270 Mbps under simulated operational conditions. The SNSPD system has been deployed at the Palomar Observatory's 200-inch Hale telescope and is ready for DSOC operations to begin shortly after Psyche's launch.

In the future, instead of relying on research telescopes like that at Palomar, a functional optical DSN will need a dedicated global network of large-scale telescopes. Thus, the RF/Optical Hybrid (RFOH) project has mounted mirror segments on a DSN radio dish to form an optical telescope. The RFOH telescope will collect signals from the DSOC flight transmitter, couple them into a multimode fiber, and route them to an SNSPD array. The 16-channel SNSPD array was fabricated at MDL and delivered to the DSN's Goldstone Complex in July 2022. A follow-on project would deploy a larger mirror and require much larger and faster detectors. These demonstrations will pave the way for future radio/optical hybrid receivers as part of a functional optical DSN.

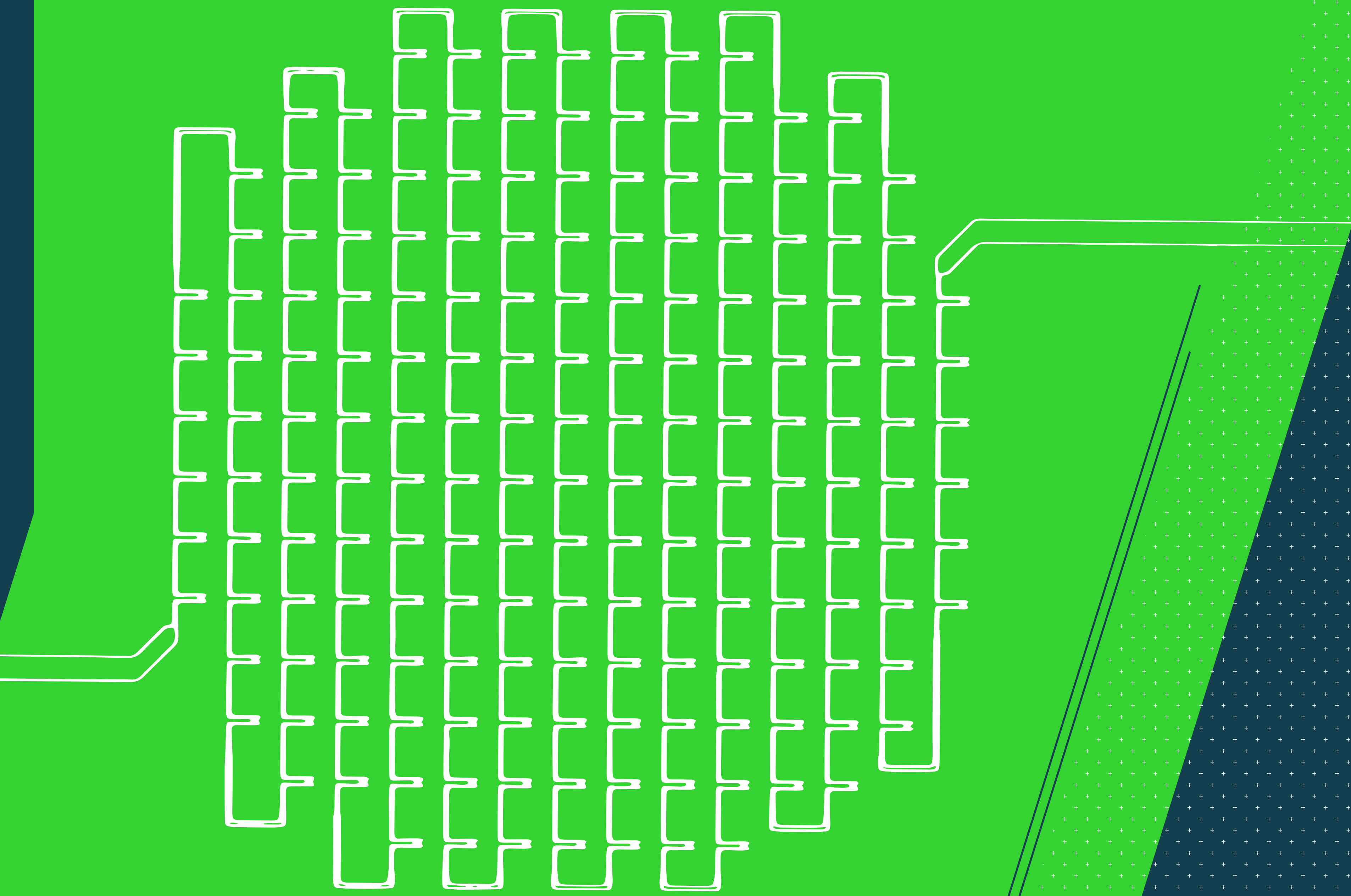
LLCD, DSOC, and RFOH are technology demonstrations. The next step, the first fully operational optical communication project to use SNSPDs, will be Optical to Orion (O2O). O2O will establish optical links with the Orion spacecraft as part of the Artemis II mission, NASA's first crewed mission to the Moon since the Apollo program.

The Orion spacecraft will carry four astronauts around the Moon and back to Earth. The spacecraft will also carry a flight transceiver to send and receive laser signals, and ground stations on Earth will hand off communication to the spacecraft. MDL developed SNSPD arrays for O2O ground stations at JPL's Table Mountain Facility and at the White Sands terminal. The O2O project will use optical communication to reach data rates that could allow future high-definition video from Mars.

DSOC array packaging

Demonstrating very-long-range optical communication

SEED GAME-CHANGING CAPABILITIES



MDL TECHNOLOGY INNOVATIONS SUPPORT NEW MISSIONS AND INCREASE SCIENCE RETURNS

From e-beam fabrication techniques to new superconducting materials, MDL has been responsible for innovations and technologies that have enabled scientific discovery for over three decades. Some of these technologies are already key parts of missions due to be launched in the next few years. Others give a glimpse into how future developments will open up new opportunities to better understand the universe, whether it be through studying weather patterns on Earth, looking for life on ocean worlds, or peering into the farthest corners of the universe.

NASA's EYES

E-BEAM LITHOGRAPHY PATTERNING AND FABRICATION CAPABILITIES HAVE EXISTED ALMOST AS LONG AS MDL ITSELF

Dan Wilson holding a prototype AVIRIS-5 grating on an e-beam cassette

E-BEAM

E-beam Fabrication Facility

MDL's e-beam lithography patterning and fabrication capabilities are foundational to MDL's past, present, and future success: the lab's first e-beam lithography tool was installed in 1989, shortly after MDL's dedication, and new systems were added in 2000 and 2017. E-beam fabrication at MDL has two major objectives: to provide unique e-beam-fabricated optical components that can enable NASA instruments and devices and thus return breakthrough science, and to advance the state of the art in diffractive/nanostructured optical components and instruments.

Diffractive Optics

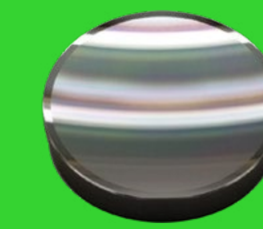
To meet these objectives, research and development activities are conducted, and new fabrication methods are continuously developed to meet increasingly complex instrument requirements. For example, in the 90s, MDL developed novel grayscale e-beam lithography techniques for various materials, enabling the fabrication of general diffractive optical elements. Subsequently, methods were developed for fabricating these grayscale surfaces on convex and concave surfaces, including up to 10 mm of height variation. This non-typical use of e-beam lithography required the development of custom e-beam calibration techniques, substrate mounting fixtures, tailored patterns, pattern preparation software, and optical characterization and verification test equipment. MDL's unique capability to fabricate diffractive optics, in particular gratings on curved substrates, has enabled major advances in JPL's long, successful program of developing hyperspectral imaging spectrometers for a variety of Earth and planetary remote sensing applications.

Additionally, over the past two decades, MDL's expertise has expanded to ever-larger components. In one notable comparison, the concave grating fabricated for the Earth Mineral Dust Source Investigation (EMIT), launched in 2022, is 92 mm in diameter, ~sixfold greater than the diameter of the convex grating for the Hyperion spectrometer on the Earth-Observing-1 satellite launched in 2000. The e-beam team also works closely with the black silicon slit/mask fabrication team, as well as many other MDL researchers developing novel nanoscale fabrication processes, to enable innovative science instruments.

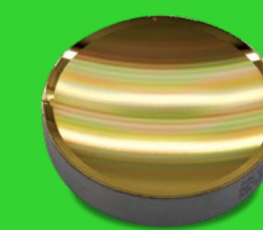
Instrument Components

MDL's e-beam capabilities fulfill an important role for JPL and NASA by providing unique components that are not available from commercial suppliers, and its fingerprints are on myriad missions. Instruments and missions enabled by e-beam-fabricated gratings include Hyperion; the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM); the Advanced Responsive Tactically Effective Military Imaging Spectrometer; the Moon Mineralogy Mapper; the Compact Wide-swath Imaging Spectrometer (CWIS), which is the prototype for EMIT; and the Hyperspectral Thermal Emission Spectrometer (HyTES), among many others. The Perseverance rover on Mars has two instruments, SHERLOC and PIXL, that also rely on e-beam-fabricated components from MDL: SHERLOC contains a UV grating that produces excellent spectra with near-theoretical-maximum diffraction efficiency and negligible scatter, and PIXL contains two spot array computer-generated holograms (CGHs) to aid in sensor head positioning.

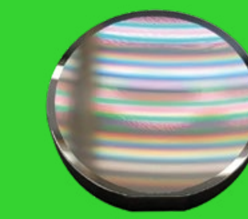
E-BEAM-FABRICATED COMPONENTS FROM MDL HAVE HELPED US UNDERSTAND THE UNIVERSE, FROM EARTH TO DEEP SPACE



Concave grating for EMIT

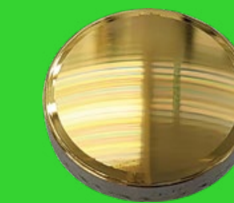


Concave grating for MISE

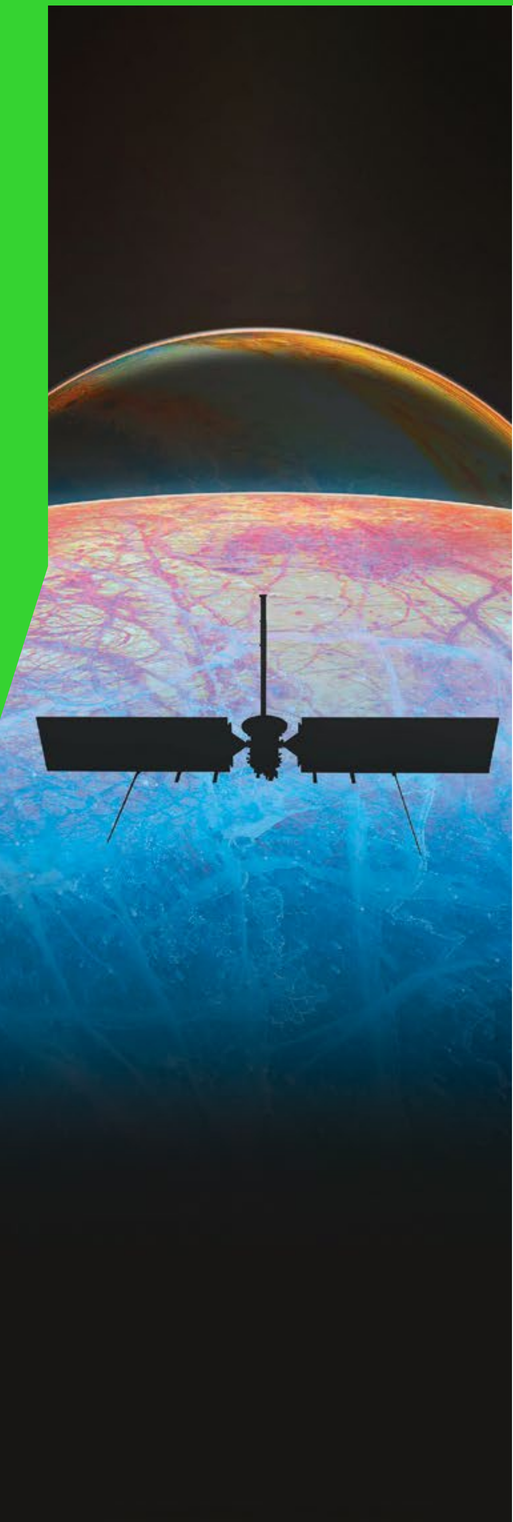


Concave grating for Carbon Mapper

Ultraviolet grating for Mars 2020 SHERLOC



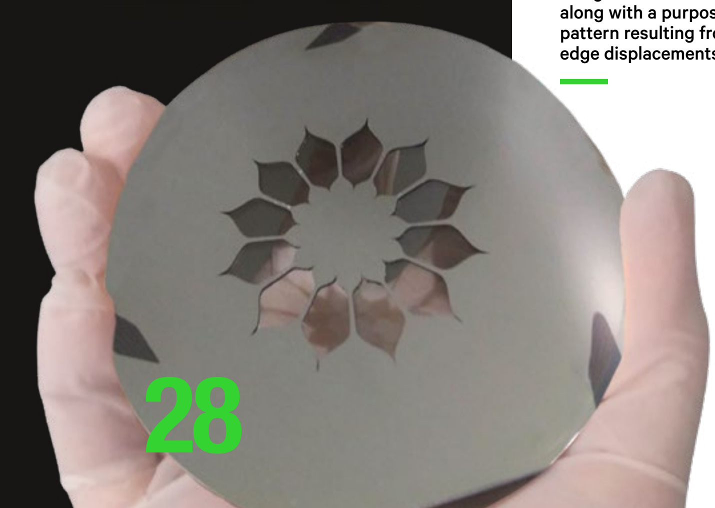
Convex grating for HVM3



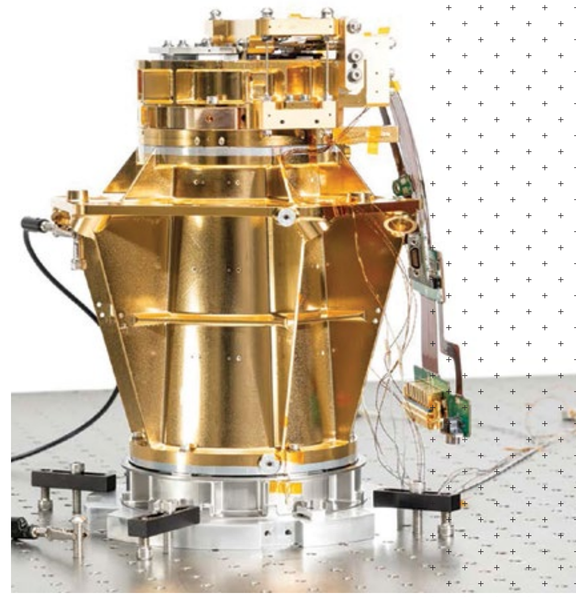
OPTICAL COMPONENTS FROM MDL HAVE GONE TO THE MOON AND MARS AND WILL SOON HEAD FOR JUPITER

Essential Components for Current and Near-future Missions

Recent and future missions also benefit from MDL's e-beam fabrication capabilities. The High-resolution Volatiles and Minerals Moon Mapper (HVM3) imaging spectrometer, scheduled for launch in November 2023 as part of the Lunar Trailblazer mission, contains a custom e-beam-fabricated convex grating. The Mapping Imaging Spectrometer for Europa (MISE) Dyson spectrometer on the Europa Clipper, set to launch in 2024, contains a custom e-beam-fabricated concave grating. The James Webb Space Telescope's Near-infrared Camera (NIRCam) (launched in 2021 and now in operation) contains e-beam-fabricated half-tone grayscale occulting masks fabricated in 2011. The Coronagraph Instrument (CGI) on the Nancy Grace Roman Space Telescope, planned for launch in 2027, contains multiple focal plane occulting masks that were fabricated by combining binary metal and grayscale dielectric e-beam lithography.



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



SBG Spectrometer prototype

New Elements in Development

Current e-beam projects include fabricating gratings and slits for Carbon Mapper, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)-5, and the Surface Biology and Geology (SBG) spectrometer; echelle gratings for the Palomar Habitable Zone Planet Finder (PARVI) and iLocater; a grayscale-profiled mirror for exoplanet detection by the Telescope for Orbit Locus Interferometric Monitoring of our Astronomical Neighborhood (TOLIMAN); UV gratings on aspheric substrates, and a variety of specialized masks in support of future exoplanet imaging/spectroscopy instruments. Balancing flight deliveries with research and development activities while continuing to develop fabrication, design/simulation, and optical characterization techniques is challenging but rewarding, and the proof is in the many scientific advances that have resulted. From Earth's own atmosphere to the farthest reaches of the known universe, the insights that NASA has gathered from robust observations are often facilitated by the custom components created via e-beam fabrication at MDL.

SBG EARTH FROM AFAR

MDL WILL HELP PRODUCE THE SPECTROMETERS NEEDED TO GENERATE SBG DATA

NASA's next Surface Biology and Geology Designated Observable will help better understand Earth's surface condition

Understanding the complex interactions between Earth's atmosphere and surface is critical not only for short-term predictions of future conditions but also, and more importantly, for the longer-term understanding of the effects of climate change.

Every ten years, The National Academies of Sciences, Engineering, and Medicine undertake surveys in each main scientific area to prioritize areas for development and suggest future NASA missions for the next decade. The most recent Decadal Survey for Earth Sciences, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space," was published in 2018. The Survey recommended a set of Earth observation satellites that would work together with existing or already-planned missions to give an integrated view of Earth.

One critical target is Earth's surface, which defines the Surface Biology and Geology (SBG) Designated Observable. This observable is strongly affected by changes in climate, and it will be considered when designing the Earth Observatory system planned for the late 2020s. Consequently, the NASA Earth Sciences Division organized an SBG architecture study involving various NASA centers, including JPL.

The study was tasked with reviewing a wide range of possible mission architectures that could address key scientific needs and recommending the most appropriate and cost-effective options to NASA.

SBG not only looks at Earth's surface but also the radiation emitted from the surface, a key factor in the energy balance of the planet. It could yield many benefits, including detailed observations of plant life on land and on ocean surfaces, as well as information on the risk of wildfires and other hazards, whether natural (e.g., landslides) or man-made.

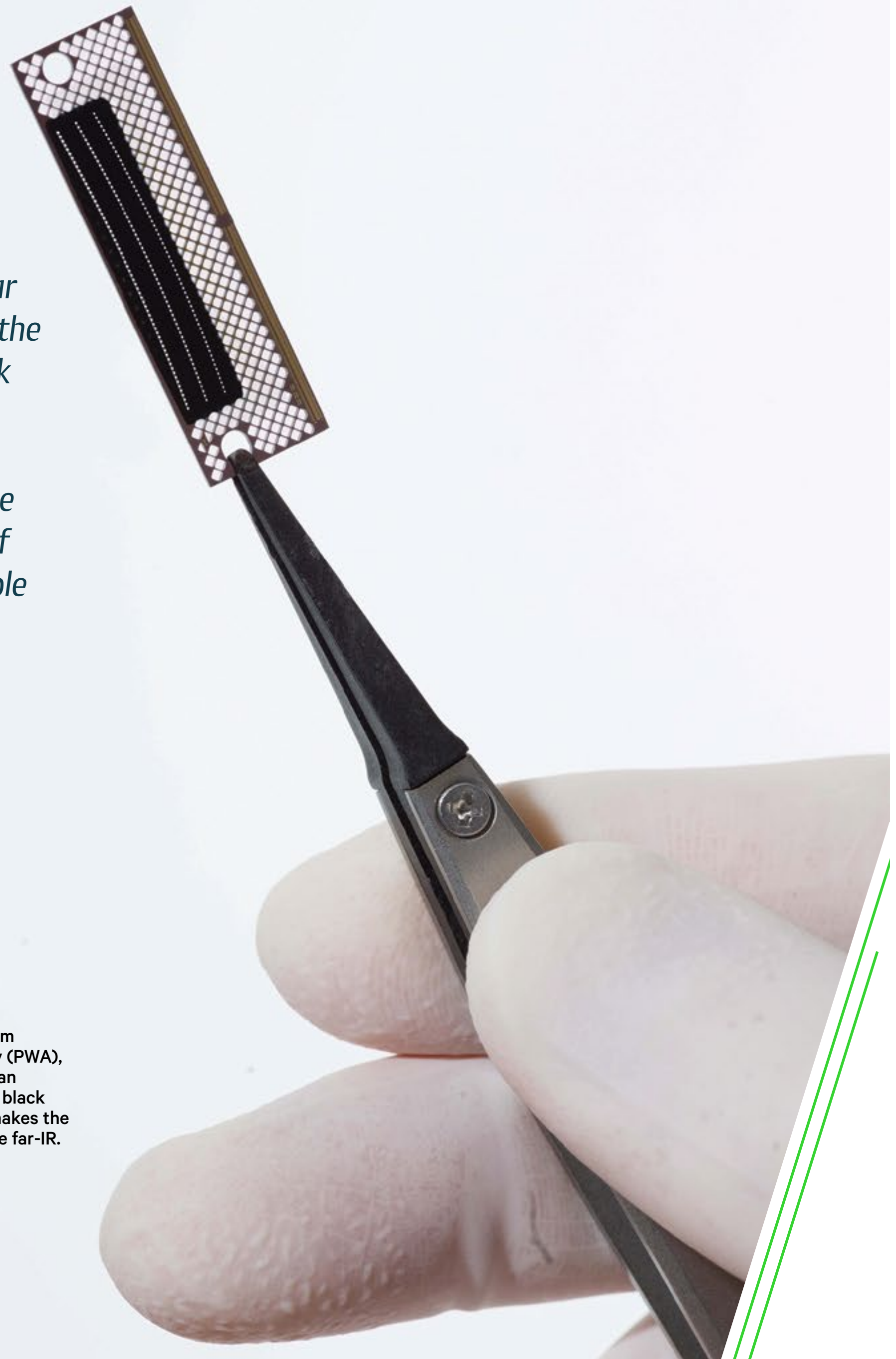
Acquiring a comprehensive dataset on Earth's surface and its interaction with the atmosphere will require observing a very large proportion of the surface spectroscopically in the visible to shortwave IR range, as well as taking thermal IR images. JPL and MDL have an extensive and successful record of producing Dyson imaging spectrometers, from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) to the Earth Surface Mineral Dust Source Investigation (EMIT), that will be used to develop the instruments that will provide these data. The JPL concept being developed uses a matched pair of spectrometers based on the EMIT design and will cover a swath of 185 km across with a resolution of 30 meters. Building on this heritage will be a cost-effective and technically efficient answer to the difficult but essential SBG challenge.

(RADIATION) BUDGETING IN THE 21ST CENTURY

DEMETER IS A LOW-COST, LOW-RISK SOLUTION TO MONITORING EARTH'S RADIATION BUDGET

Earth's radiation budget (ERB) is the balance between the solar energy that reaches Earth and the energy that Earth radiates back into space. In the face of global warming, ERB is important to track; ERB observations provide crucial constraints on models of future warming, and they enable a process-level understanding of the energy flow within the climate system and how that energy flow is changing.

BUILDING ON MDL'S FOCAL PLANE MODULE FOR PREFIRE



The focal plane module (FPM) consists of a custom thermopile detector chip, a printed wire assembly (PWA), a molybdenum and ceramic mounting block, and an aluminum housing. An optical coating called gold black covers the 64 x 3 element thermopile array and makes the FPM sensitive to light from the visible through the far-IR.

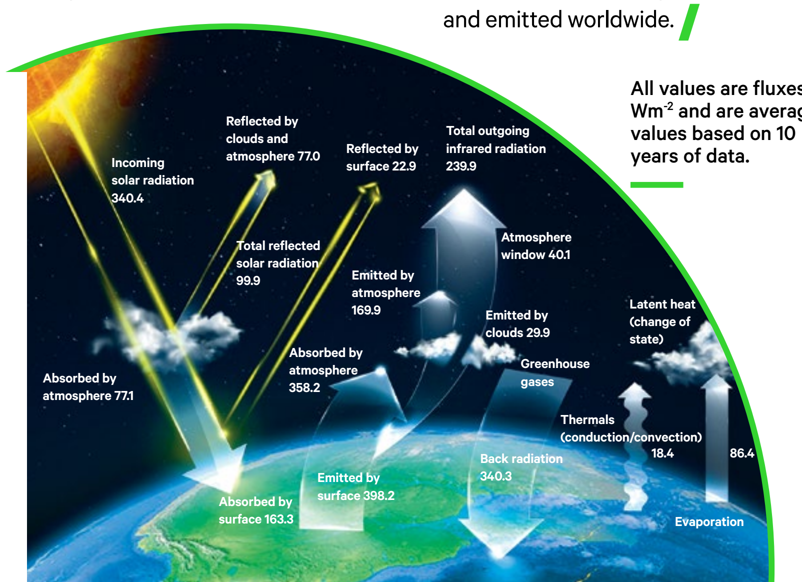
DEMETER

Picture of the vacuum testbed used to measure the performance of the FPM. A blackbody (right) shines IR radiation through a window into the vacuum chamber where the FPM is mounted. Electronics not shown control the FPM and record the signals from each of the pixels.

Since 2000, ERB data have been generated via the Clouds and the Earth's Radiant Energy System (CERES) project, which has provided the longest continuous global observational record of ERB currently available. However, CERES is part of an instrument class that is massive (~50 kg), requires substantial energy (~50 W), and contains complex scanning mechanisms. Such instruments must be hosted payloads on large observatories (~3,000 kg) and require budgets of $150 million or more. A new low-cost, low-risk platform is needed, and it is being developed via NASA Langley's Instrument Incubator Project DEMonstrating the Emerging Technology for measuring the Earth's Radiation (DEMETER).

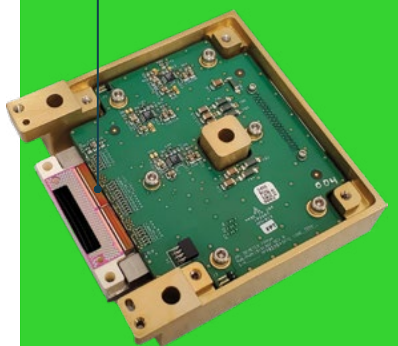
DEMETER is a free-flying small satellite (sensorcraft) solution that will represent a tenfold reduction in cost, risk and power requirements compared with the current state of the art. The DEMETER sensorcraft approach integrates non-scanning wide-field-angle telescopes and two-dimensional detector array sensor/payload elements with NovaWurks' "building block" platform. This strategy yields an intelligent, integrated, and affordable solution that is far more efficient and will enable persistent and sustainable observations of ERB. DEMETER was initially funded in 2020 by the NASA Earth Science Technology Office (ESTO) Instrument Incubation Program (IIP). Since then, DEMETER's TRL has increased, and prototypes of its components have been developed.

The prototype was built upon the MDL-fabricated focal plane module (FPM) originally developed for NASA's Polar Radiant Energy in the Far Infrared Experiment (PREFIRE), but with modifications to reduce the detectivity and responsivity to avoid pixel saturation. The instrument's <25 km spatial resolution will enable better "clear-sky" identification and reporting using smaller spatial grids. The prototype FPM met the key performance requirement of noise equivalence radiation in select pixels, and other lessons were learned that will facilitate an even better-performing FPM if a second version is built. The current strategy for DEMETER is to fly the prototype in the near future and eventually progress to a constellation of three DEMETER instruments that could provide global ERB monitoring and help better understand how energy is absorbed and emitted worldwide.

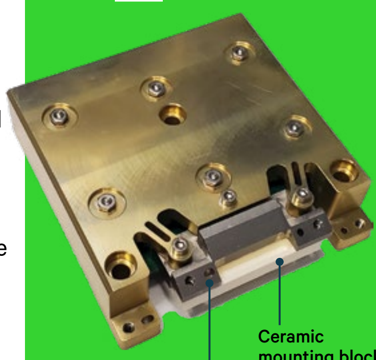


All values are fluxes in Wm^{-2} and are average values based on 10 years of data.

Detector chip without gold black



Focal plane module



Backside focal plane module

THE INSTRUMENT MEASURES THE REFLECTED SOLAR AND EMITTED THERMAL ENERGY LEAVING THE EARTH

SEED

PIRS FIRED UP

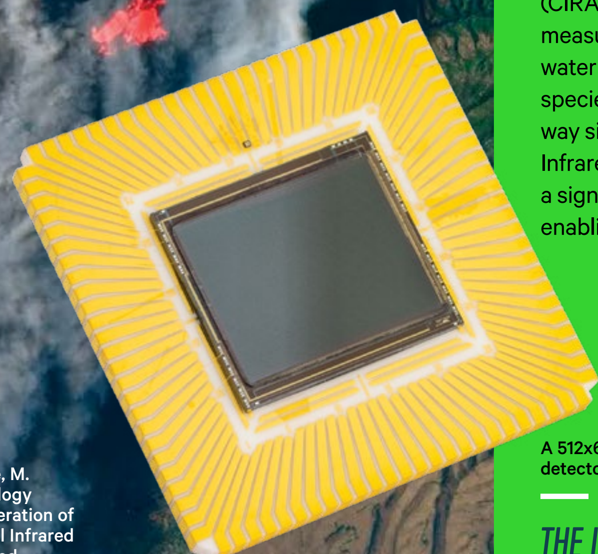
Advances in IR detectors and immersion grating technology at MDL have enabled a new generation of IR grating spectrometers that will support meteorology and atmospheric composition measurements in future NASA Earth science missions [1], such as those aimed at understanding how wildfires start and spread.

[1]T. S. Pagano, D. Johnson, J. Mcguire, M. Schwochert and D. Z. Ting, "Technology Maturation Efforts for the Next Generation of Grating Spectrometer Hyperspectral Infrared Sounders," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, (2022) doi: 10.1109/JSTARS.2022.3165168.

JPL's Pyro-atmosphere Infrared Sounder (PIRS) will monitor fire weather conditions in three dimensions and with sub-km spatial resolution

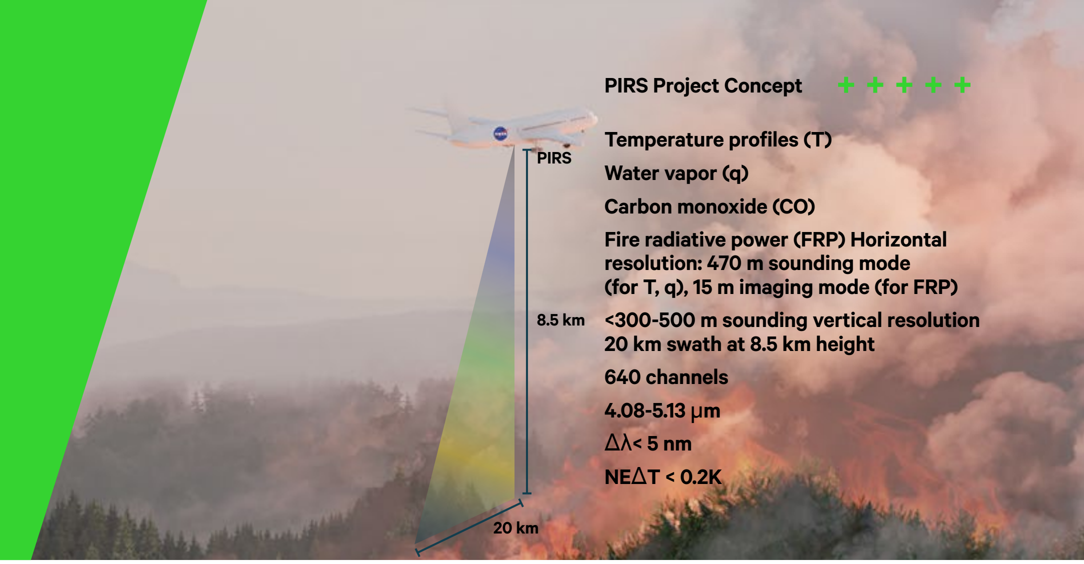
JPL's high operating temperature-barrier infrared detectors (HOT-BIRDs) offer better uniformity with a higher operating temperature, resulting in lower power than traditional HgCdTe detectors. JPL's e-beam etching processes have enabled the fabrication of a grating on the substrate of a prism, resulting in an immersion grating, or "grism." The grism allows the grating spectrometer to be smaller and lighter. JPL's black silicon process was used to make the entrance slit to the spectrometer, reducing stray light effects.

These technologies have been incorporated into an IR grating spectrometer called the CubeSat Infrared Atmospheric Sounder (CIRAS). CIRAS is designed to measure the temperature profiles, water vapor profiles, and trace gas species in Earth's atmosphere in a way similar to JPL's Atmospheric Infrared Sounder (AIRS) but in a significantly smaller package, enabling flight in a CubeSat.



A 512x640 element HOT-BIRD detector array

THE INSTRUMENT IS ENABLED BY MDL'S GRATING, BLACK SILICON, AND DETECTOR TECHNOLOGY



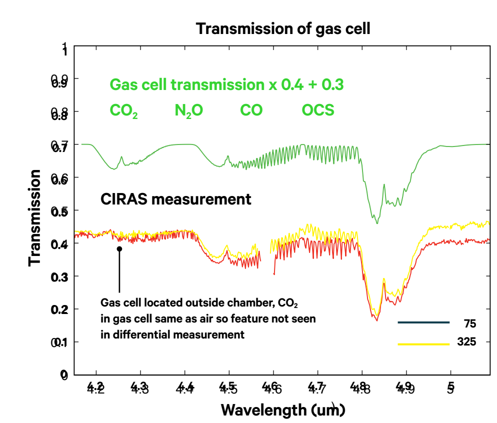
This advance not only greatly reduces the cost of making critical meteorological measurements from space but also allows these measurements to be made at different times of day and more frequently through flight in a constellation.

The new data are expected to improve weather forecasts, particularly in the late afternoon, when severe storms form. New measurements are also possible with CIRAS to further improve weather forecasts, including 3D winds, by measuring the motion vectors of water vapor profiles.

In 2021 and 2022, JPL completed the integration and thermal vacuum testing of the CIRAS spectrometer. The instrument included the complete optical system, built to scale by Ball Aerospace, and incorporated the JPL-developed grism and entrance slit that operates at 190 K. The instrument also included a full-scale 512x640 element HOT-BIRD detector array housed in an integrated Dewar cryocooler assembly (IDCA) and operated at 115 K.

Testing showed excellent spatial and spectral performance, meeting all requirements. The figure below shows the results from a measurement of a gas cell showing all the expected features at the expected spectral resolution. Testing CIRAS in the relevant environment of a thermal vacuum at operational temperatures achieved TRL 5 for the system.

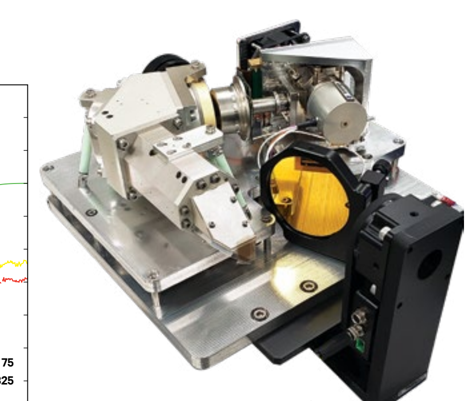
On May 18, 2023, NASA's Earth Science Technology Office (ESTO) selected the JPL proposal "Pyro-Atmosphere Infrared Sounder (PIRS): Monitoring Fire Weather Conditions with a Sub-Kilometer Spatial-Resolution Hyperspectral Infrared Sounder" as one of the first two projects for funding and development as part of its Technology Development for Support of Wildfire Science, Management, and Disaster Mitigation Program.



Monitoring fire weather conditions with a sub-kilometer spatial-resolution hyperspectral infrared sounder

THE TECHNOLOGY IS PROVEN ON THE GROUND AND WILL NEXT BE TESTED ON BOARD AN AIRCRAFT

The PIRS project will retrofit the CIRAS brassboard for flight on an aircraft to measure the temperature and water vapor profiles, radiative potential and carbon monoxide over wildfires to characterize the convective environment around and near them. The effort will also vibration test the PIRS, achieving TRL 6 for a future spaceflight program. The PIRS will be able to detect the strong, deep convection that can occur with fires; this convection can make fire suppression activity more difficult and unpredictable and lead to fire spotting in surrounding areas. Information gleaned from PIRS will help improve firefighting efforts.



The CIRAS brassboard includes flight-design optics and HOT-BIRD FPA

PRIMA FIRST LIGHT

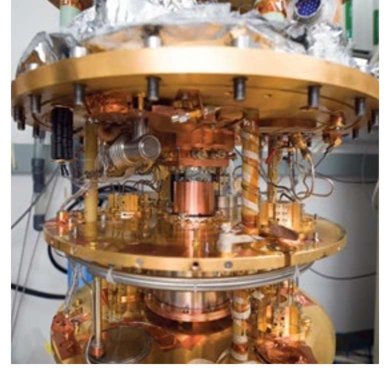
The Probe Far Infrared Mission for Astrophysics will be the first far-IR space telescope

Galileo first turned his telescope toward the sky in the early 17th century, effectively marking the start of detailed observations of the solar system. However, even then, it soon became apparent that image clarity was limited; Earth-based observations are difficult due to dust, water, clouds, and temperature changes, even though Earth's atmosphere is transparent to many wavelengths of light.

Consequently, the idea of a space-based telescope above Earth's atmosphere was first proposed in the 1920s. Although the first space telescope launched much later in 1968, it was the Hubble Space Telescope (HST) that enjoyed the greatest fame until recently. The HST was launched in 1990 on the Space Shuttle Discovery (STS-31) and put into low Earth orbit approximately 330 miles above Earth. Its view, unaffected by Earth's atmosphere, has produced stunning images and monumental insights.

Unfortunately, the furthest and oldest parts of the universe remain obscured, not by an atmosphere, but by dust. However, just as red light penetrates dust more easily than other visible wavelengths, far-IR light can see through dust completely.

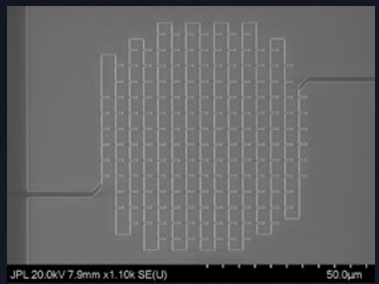
A far-IR space telescope does not exist. The need for such a telescope was prioritized in the Decadal Survey, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," published in 2021.



In response, Goddard, JPL, and Caltech are developing a joint mission concept. That concept, the Probe Far Infrared Mission for Astrophysics (PRIMA), is a concept for a cryogenic space telescope mission in the far-IR (25–260 µm) and was submitted in early 2023 in response to NASA's Announcement of Opportunity for an Astrophysics Probe Explorer (APEX) mission.

To achieve exceptional performance, Goddard, JPL, and Caltech homed in on the use of MDL technology, developed over more than 20 years, that would yield single-photon sensitivity for a cryogenic detector, the magnetic kinetic inductance detector (MKID).

Although enabled by this technology, the proposed mission is not simply technology driven. In March 2022, a community workshop convened in Pasadena to establish and prioritize a portfolio of scientific objectives in response to the Decadal Survey priorities. These objectives included: exoplanets, star and planet formation, nearby cosmic ecosystems, the evolution of galaxies and the supermassive black holes at their centers, and dust and metals in the universe. This planning allowed the first stage of determining scientific priorities and technical capabilities and further refined the possibilities for the mission concept. It is undoubtedly the start of an exciting journey.

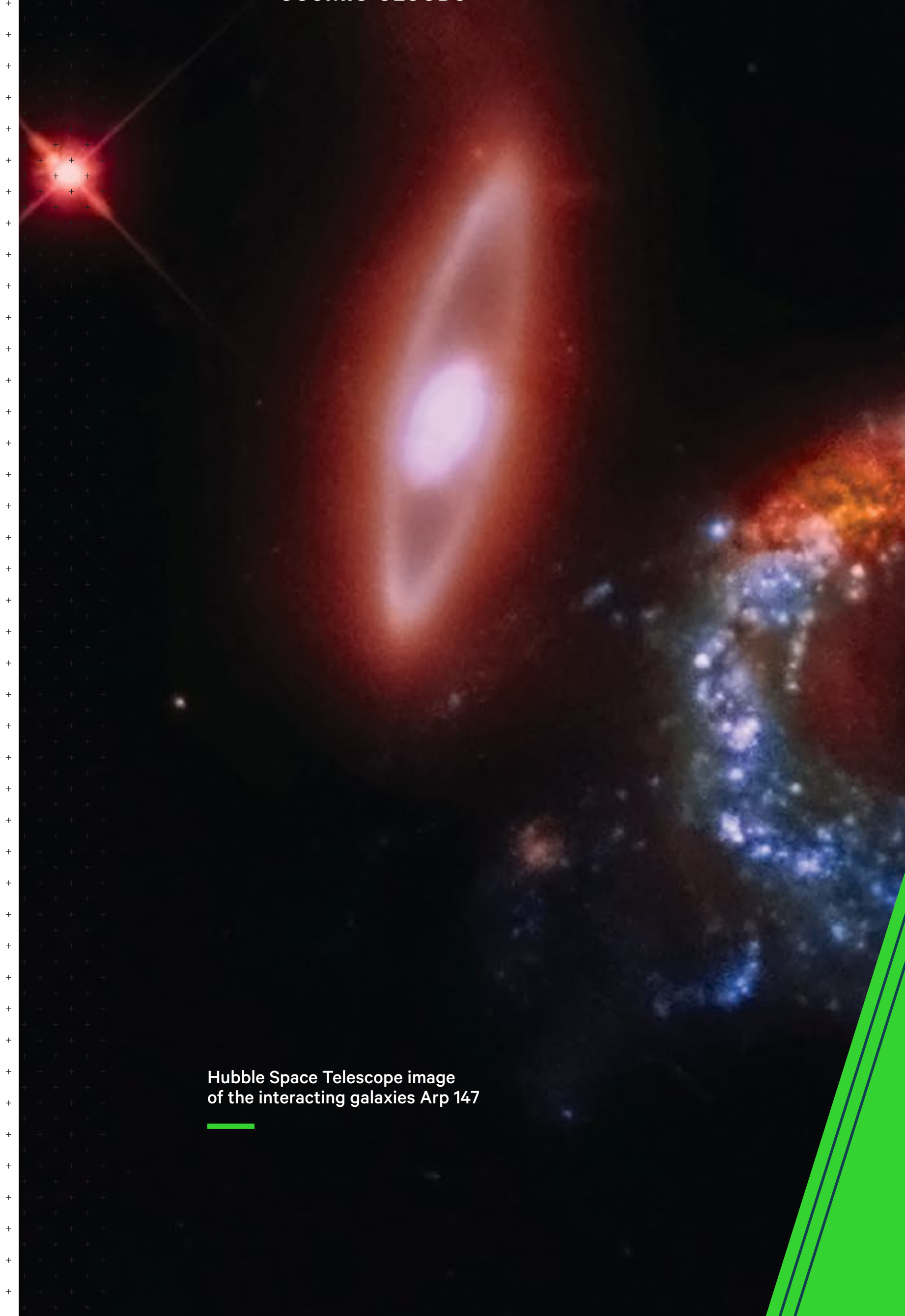


MDL MKID TECHNOLOGY YIELDS SINGLE-PHOTON SENSITIVITY

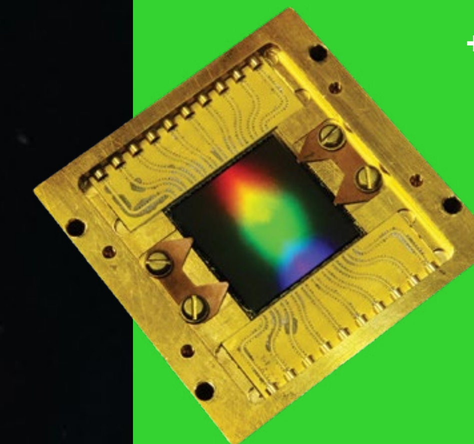
THE TELESCOPE'S FAR-IR WAVELENGTHS WILL SEE THROUGH COSMIC DUST

MKIDs BEHIND THE VEIL

MAGNETIC KINETIC INDUCTANCE DETECTORS WILL HELP SEE THROUGH COSMIC CLOUDS



Hubble Space Telescope image of the interacting galaxies Arp 147

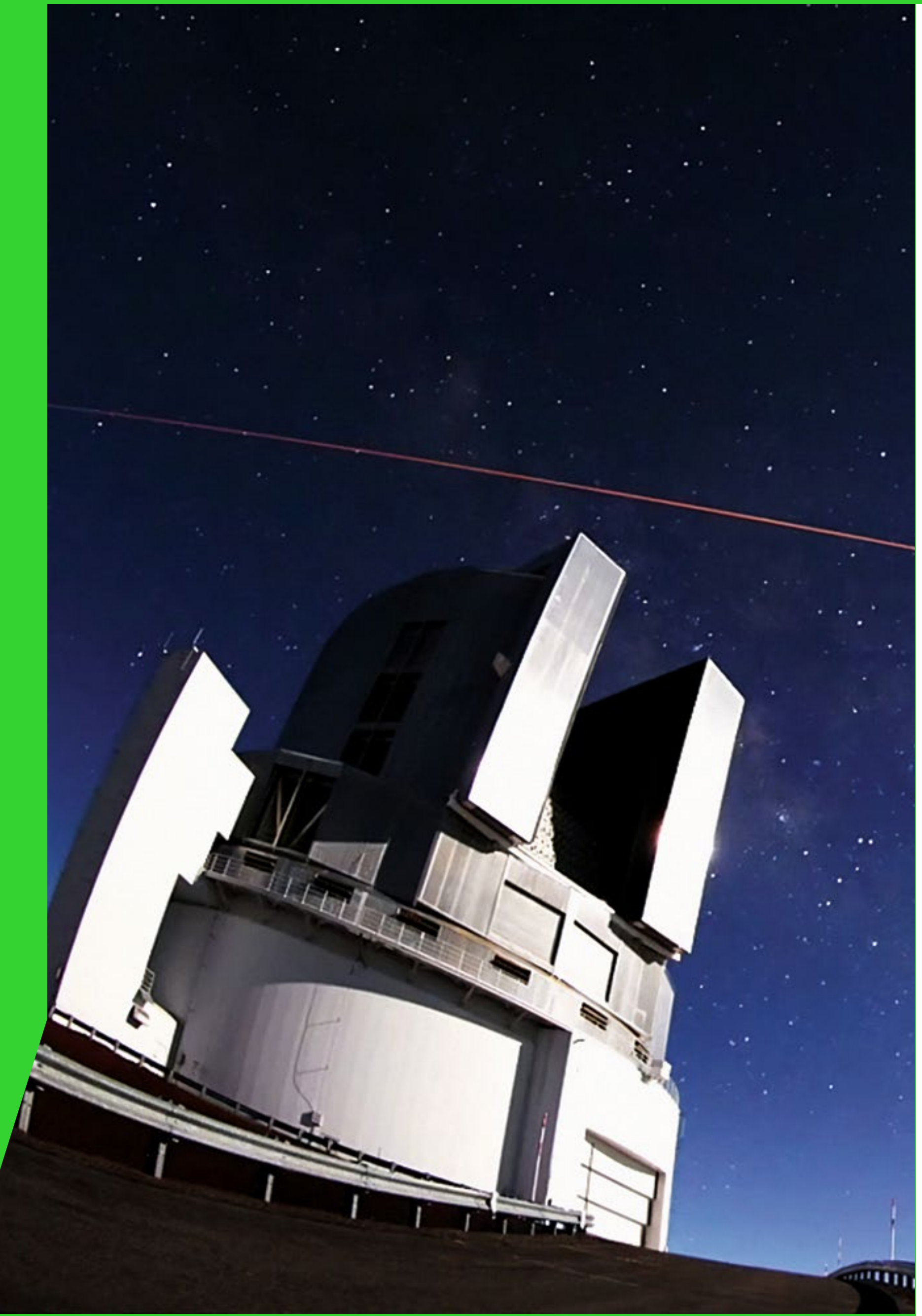


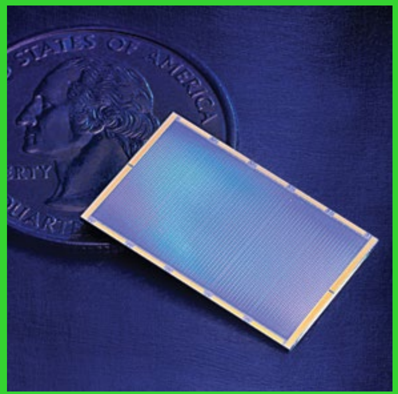
20 kpix MKID array, the largest superconducting detector in the world, used in the MEC instrument

The universe is dynamic: new stars are born shrouded in clouds of dust, exoplanets coalesce around these newborn stars, and the universe as a whole is expanding

Currently, just one IR-detecting tool, the magnetic kinetic inductance detector (MKID), promises to enable better views of all these phenomena thanks to its exquisite sensitivity, low noise equivalent power, ability to be frequency multiplexed, and the resultant high mapping speed. MKIDs are superconducting resonators: the material they are made from allows them to detect and resolve single photons, and their ability to be multiplexed simplifies wiring and reduces the heat load, a critical factor for operating at cryogenic temperatures.

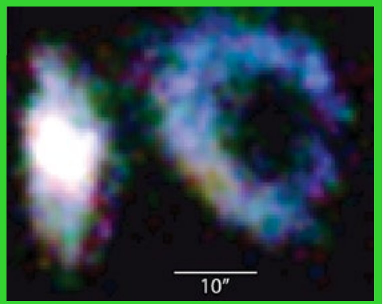
The dust clouds that obscure stellar nurseries are transparent in IR, and the light the dust absorbs from these newborn stars is also emitted in the far-IR. Consequently, these areas of the universe are very bright in IR, even if they are hidden in the visible and UV portions of the spectrum. Consequently, MKIDs can see beyond the clouds and provide a highly detailed view and better understanding of how stars are born.





Near-IR detector chip of 10k pixel DARKNESS array: 80 X 125 pixels with 5 microwave drive lines

JPL delivered 20k pixel devices for exoplanet observations at the Subaru telescope (MKID Exoplanet Camera, aka MEC)



A mosaic of the interacting galaxies Arp 147 made with ARCONS on the Palomar 200-inch telescope

The sensitivity of MKIDs to single photons means that they can also directly observe faint exoplanets orbiting other suns, a marked improvement over the indirect observations of a star dimming when a large exoplanet passes between it and Earth. Moreover, MKIDs can reveal what these exoplanets are made of. With thousands of exoplanets already observed and countless others waiting to be discovered, MKIDs will yield new information about the environments on other worlds and perhaps also uncover information that could apply to Earth's own formation.

As the universe expands, the light emitted by receding stars and galaxies redshifts into the IR and far-IR. The ability of MKIDs to detect IR and far-IR light, coupled with their single-photon sensitivity, will enable them to collect the faintest light from the farthest galaxies at the edge of the universe. In this way, they will facilitate a new view into the earliest days of the universe.

MDL has been developing MKID technology for over two decades, and advances in materials and fabrication processes have been crucial to improving MKID performance. The deposition and patterning of novel materials has allowed the creation of MKID integrated circuits, which has improved their spectral response and quantum efficiency. Small-volume, highly sensitive aluminum MKIDs have also been fabricated. Although MKIDs have not yet been deployed on airborne or spaceborne missions, MKID arrays are already in use on Earth and are advancing knowledge about exoplanets. In the next stage of evolution for this technology, MKIDs are baselined for a joint MDL/Goddard mission concept for a far-IR observatory, which was mentioned as a priority in NASA's 2020 Decadal Survey on Astronomy and Astrophysics.

MKIDs for far-infrared astronomy

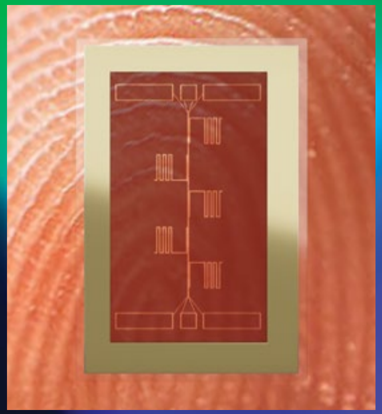
MgB_2 SUPERCONDUCTING THIN FILMS SUPERCHARGE MDL DEVICES

Magnesium diboride could one day enable exquisitely sensitive detectors that have lower cooling requirements than ever

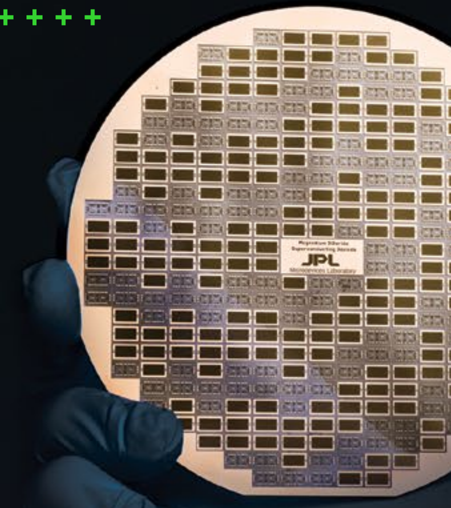
Most superconducting materials only behave as such near 4 K, so some research has aimed to identify materials that superconduct at higher temperatures. In 2001, magnesium diboride (MgB_2) was shown to behave as a superconductor at high temperatures, and research on MgB_2 films at MDL began in 2017. The first in-house superconducting films at MDL were demonstrated in 2018.

Recently, MDL teams developed MgB_2 thin films with a critical temperature as high as 37 K. This advance has important implications since a space cryocooler operating at 4 K requires 100-fold more power than one operating at 20 K, with attendant significant instrument costs. Therefore, using MgB_2 thin films that function at 10-20 K 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-IR 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 THz 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" 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 radiofrequency (RF) loss in the material.



NEW SUPERCONDUCTING DEVICES PROMISE TO REVOLUTIONIZE ASTRONOMY

The next step will be to demonstrate practical devices with these films, including kinetic inductance bolometers, single-photon detectors for optical communications in space, and THz mixers for high-resolution spectroscopy. MDL researchers are also developing a family of devices utilizing nonlinear kinetic inductance towards THz 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.

Advances in magnesium diboride technologies

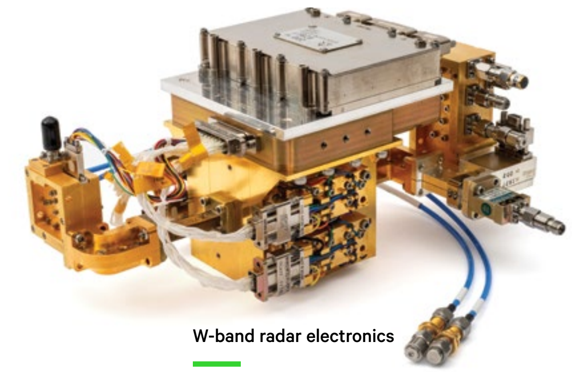
GLOBAL OBSERVATIONS OF CLOUDS AND PRECIPITATION

Constellations of MiniSats bearing CloudCubes may one day provide frequent, real-time monitoring of the Earth's atmosphere and climate in three dimensions

CloudCube WILL HELP MONITOR THE EARTH'S ATMOSPHERE IN UNPRECEDENTED DETAIL

CloudCube

A comprehensive understanding of climate change requires frequent, detailed measurements of the processes that occur in the Earth's atmosphere. Data from current airborne and spaceborne instruments provide some of this information, but spatial and temporal gaps remain.



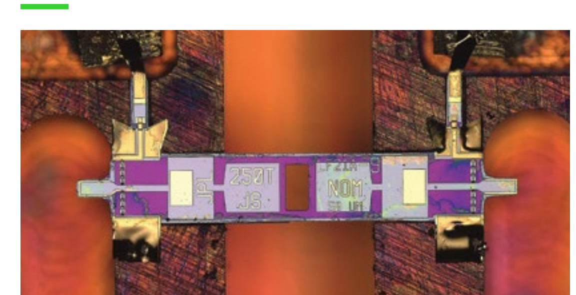
W-band radar electronics

One approach to filling these gaps is CloudCube technology, a compact system that for the first time combines Ka-, W-, and G-band (35/94/240 GHz, respectively) radar bands in a single instrument, so that the instrument's mass, power, size, and recurring costs can be lower than that of using multiple separate radar instruments for each band. Combining radar observations in these three bands simultaneously will reveal how meteorological processes in clouds affect storms, rain, and snow that occur at different altitudes and over different regions. Additionally, studying cloud scattering properties up to such a high frequency will allow researchers to infer or constrain the distribution of cloud-particle sizes, thus improving our understanding of cloud evolution, microphysics, and radiative properties. It will also enable the clearest view yet into giant anvil clouds and the dynamics of convective storms. Because of the small size and power requirements of CloudCube, constellations of MiniSats or small spacecraft that include this technology could be deployed to monitor Earth's atmosphere with unprecedented spatiotemporal coverage. This coverage, plus the cutting-edge 3D climate models that CloudCube data will support, will improve planning for extreme weather and consequently improve public safety.

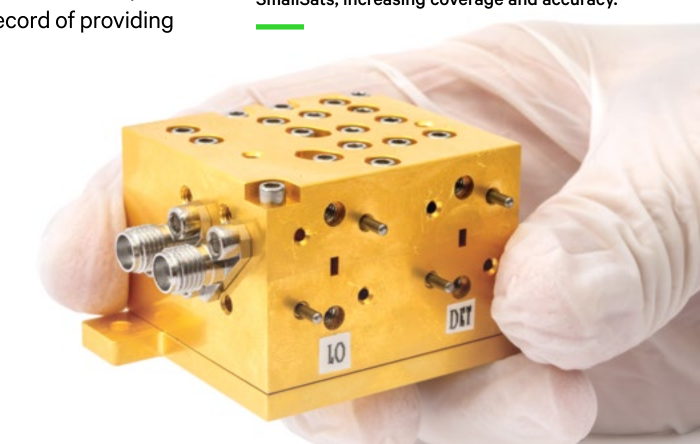
The small size and low power requirements of CloudCube come from a radar architecture that reduces the number of components and uses long-pulse compression techniques that enable low-power, high-duty-cycle transmit waveforms. The success of CloudCube's pulse compression, which was first demonstrated with NASA's Radar In a Cube (RainCube) program, depends on two major components. First is a custom MDL-fabricated Schottky diode frequency tripler capable of generating moderate continuous RF power at 240 GHz (over 120 mW). This device is part of MDL's track record of providing JPL instrument teams with customized Schottky diode frequency-multiplier devices that often achieve record efficiency and output power capability. CloudCube is the latest prototype radar to use MDL's Schottky diode process, and in 2022, the team began efforts to power-combine four of these devices to reach transmission power exceeding 0.5 W. The second component is an MDL-fabricated Schottky diode IQ mixer at 240 GHz that suppresses unwanted sideband signals. CloudCube's development was supported by the Instrument Incubator Program (IIP) of NASA's Earth Science Technology Office (ESTO).

THE INSTRUMENT COMBINES Ka-, W-, AND G-BAND RADAR IN ONE UNIT

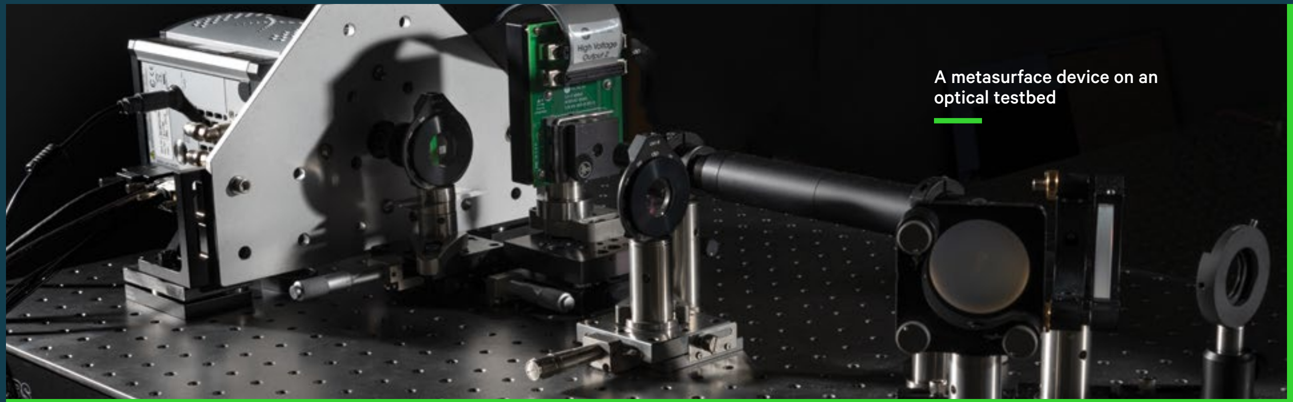
State-of-the-art high-efficiency frequency multipliers are a newly developed, compact, reliable, low-energy and high-power system on a chip.



Global observations of clouds and precipitation

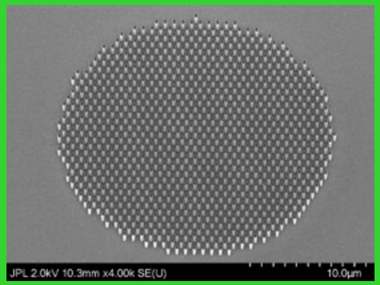


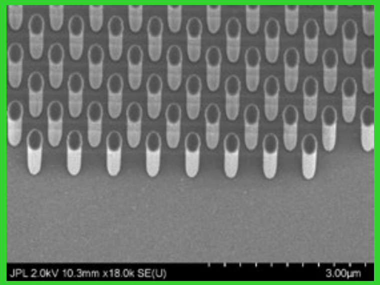
A compact down-conversion assembly module at the heart of CloudCube that will help to enable the deployment of large fleets of weather-monitoring SmallSats, increasing coverage and accuracy.



A metasurface device on an optical testbed

LIGHT, CAMERA, ACTUATION!





MDL-fabricated metasurface focal plane mask consisting of elliptical nanopillars

Metasurface-based Zernike wavefront sensors will control next-generation segmented mirror telescopes, facilitating exceptional optical quality

The next generation of space telescopes are expected to have segmented primary mirrors that must be co-phased and adjusted. To function properly, each mirror segment must be carefully controlled to support the image quality/contrast needed for accurate scientific observations. One especially challenging type of observation is the direct detection of exoplanets, especially Earth-like planets orbiting Sun-like stars. This scientific challenge is important enough to be emphasized in NASA's 2020 Astrophysics Decadal Survey. Such observations would help begin to address questions of profound importance, such as the existence of life on other planets, how planets form, and our place in the cosmos.

FUTURE MISSIONS WILL HELP DIRECTLY DETECT EXOPLANETS

However, directly imaging Earth-like exoplanets requires establishing and maintaining the optical qualities of the telescope being used to exquisite levels. Sensing this level of image quality can be provided by metasurface-based Zernike wavefront sensors, and MDL is supporting JPL-led efforts to develop sensors that can measure wavefront errors at the picometer (10^{-12} m) level. To that end, MDL has been developing metasurface focal plane masks that extend the dynamic range and sensitivity of phase-contrast wavefront sensors. By incorporating these new wavefront sensors and dynamic segments or deformable mirrors into a spaceborne telescope, the telescope can be actively controlled to stabilize the image without needing to make the entire telescope passively stable. This active control capability could significantly reduce the complexity and cost of future space telescopes and opens up new trade spaces for mission design.

MDL researchers have designed and fabricated a metasurface mask that is adapted for wavefront sensing and is part of a Zernike wavefront sensor currently installed in the Keck Planet Imager and Characterizer (KPIC) instrument at the W.M. Keck Observatory in Hawai'i. This mask has been successfully used to measure the phasing of the Keck primary mirrors, and ongoing efforts are focused on using the mask to close the feedback loop between the segments and the sensor. The initial version was a scalar Zernike sensor deployed on Keck, and MDL researchers have subsequently improved upon the design by making a vector phase mask that increases the dynamic range by using the two orthogonal polarizations of light in different ways. Future versions of the Zernike wavefront sensor will eventually be deployed on space missions, such as the Nancy Grace Roman Space Telescope, with the continued pursuit of directly observing Earth-like exoplanets.

Work on the Zernike wavefront sensor was conducted in a collaboration between MDL, JPL collaborators, Caltech, UC Santa Cruz, and the Keck Observatory. The work at JPL was funded by internal research and technology development funds.

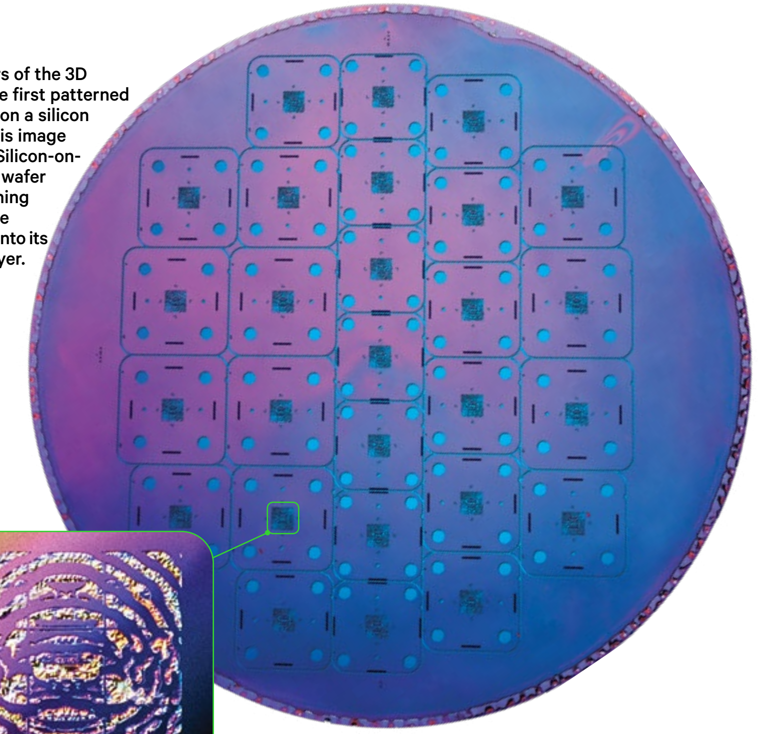
Metasurface-based Zernike wavefront sensors

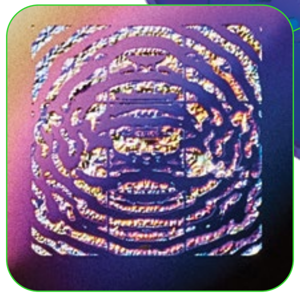
TINY EYES ON THE INFINITE

VOLUMETRIC META-OPTICS ENABLE ULTRACOMPACT DEVICES

The ability to pattern materials at subwavelength scales has laid the foundation for new generations of optical devices called meta-optics. A well-understood example of meta-optics is metasurfaces, which have spatially varying elements laid across a flat surface that can manipulate light based on light's fundamental properties of spatial, spectral, and polarization states. The ability to synthesize multiple optical functionalities into single, flat layers underpins the goal of vastly miniaturizing future space instrumentation. However, the fundamental trade-off between the efficiency of multi-functional devices and the device thinness means that currently, extremely thin devices can only do so much before their efficiency plummets.

Work at MDL is rapidly advancing the field of volumetric meta-optics, whose ambitious goal is to pattern 3D optical elements with subwavelength precision. These volumetric meta-optics are still extraordinarily thin at only a few wavelengths, yet the added thickness relative to metasurfaces is just enough to control all fundamental properties with high efficiency. They are designed with computationally efficient optimization algorithms that identify optimal shapes for a given task, a procedure referred to as inverse-design, that makes billion-dimensional optimizations tractable. Fabrication constraints are directly encoded into the optimization to ensure reliable fabricability. The resulting layer designs are then patterned on a silicon wafer, and the layers are separated and stacked to form the volumetric device. Such a device was successfully fabricated, assembled, and tested at MDL in 2022; it substantially reduces the volume and power requirements of THz spectroscopy.





The layers of the 3D device are first patterned together on a silicon wafer. This image shows a Silicon-on-Insulator wafer after etching the device patterns into its device layer.

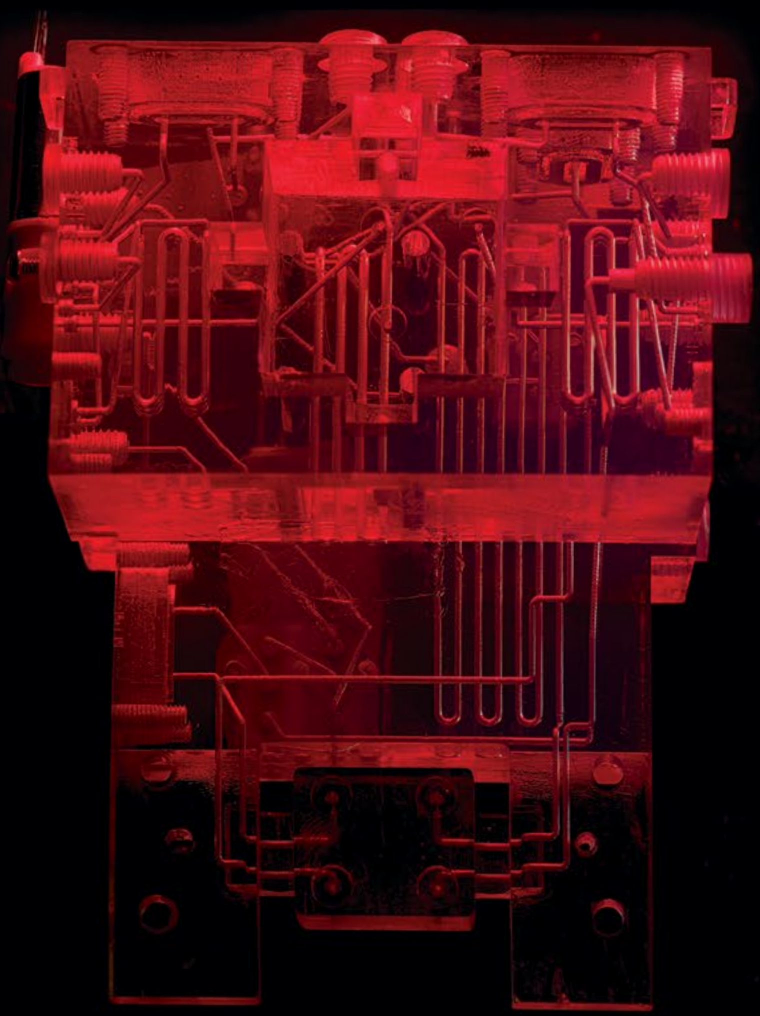
This technology offers an extraordinary pathway towards miniaturizing optical instrumentation since the efficient, customizable behavior can distill entire optical systems into a wavelength-scale cube. Presently, this work is being used to improve submillimeter-wave instrumentation by realizing an extremely compact and low-power THz spectrometer. The volumetric device can sort the spectrometer's outputs based on frequency, polarization, and spatial mode shape. It is highly efficient and entirely customizable, allowing any direct detector array to be used.

Future work will focus on realizing other submillimeter-wave devices, such as filters, multi-functional horns, and beam scanners, and scaling them to IR frequencies.

This work was funded by JPL internal Research and Technology Development funding."

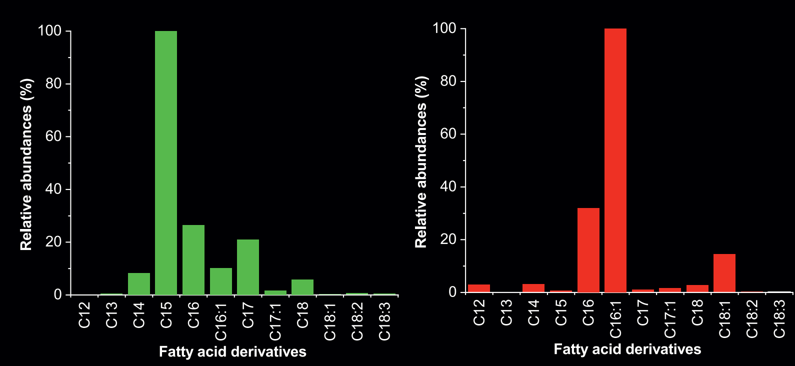
Volumetric meta-optics for wavelength-scale optical systems

SEARCHING FOR LIFE AT THE MOLECULAR LEVEL



For as long as humans have been self-aware, they have asked if there is life beyond Earth. The Organic Capillary Electrophoresis Analysis System (OCEANS) invented at MDL is designed to help answer this question by looking for key molecular signatures of life, such as amino acids and fatty acids, not just on Earth but on the ocean worlds beyond it.

THE OCEANS CHEMICAL ANALYZER CAN HELP PROTECT LIFE ON EARTH AND SEARCH FOR LIFE BEYOND IT



Biosignatures obtained for H. halophilus (green bars) and. P. haloplanktis (red bars) with CE-MS after subcritical water extraction.

OCEANS

MDL has been actively developing chemical analyzers for two decades, but OCEANS is the first spaceflight-compatible, portable liquid analyzer that can separate a sample into its components before detecting the molecules present. The system can also be connected to independent electrical, optical, and mass spectrometry systems for an even deeper understanding of a sample's composition. The entire process, from ingestion to analysis, is performed autonomously by the system, enabling it to be used on long-distance astrobiological missions to ocean worlds such as Europa and Enceladus. On such a mission, OCEANS could receive solid samples from the plumes emanating from these worlds on flyby or orbital missions, or it could receive material collected from a lander.

Developing OCEANS was not simple. A new instrument system had to be invented using 3D-printed fluidic handling manifolds and glass capillaries to analyze samples inside the system. The system had to be tested to demonstrate that it could use subcritical water extraction to transform cells or spores in a sample into chemical information that could be analyzed for molecular signs of life. This demonstration was critical since in some situations, organic matter might be in bound forms that are not amenable to direct chemical analysis.

The team also showed how the liquid output from OCEANS could be sprayed into a mass spectrometer (MS) for analysis, a process that had never been published before.

THE OCEANS SYSTEM IS PORTABLE AND SPACEFLIGHT COMPATIBLE BUT ALSO HAS APPLICATIONS ON EARTH

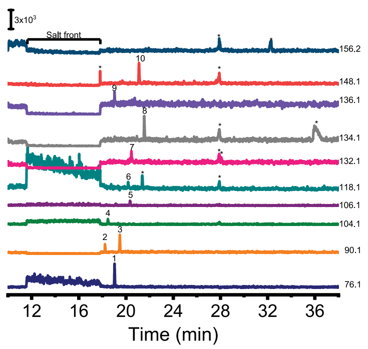
The OCEANS hardware at Mono Lake, CA during a field campaign in June 2022

Finally, they developed autonomous software that could analyze MS data and select the most promising data for return to Earth — a critical ability given the data volume limitations on such a mission.

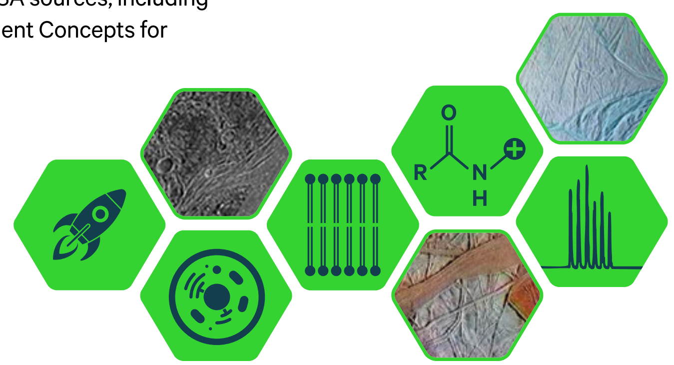
In 2022, the entire OCEANS hardware suite was completed, instrument function was validated on cell cultures, and a full system demonstration was completed at Mono Lake, California. These analyses yielded significant advances in characterizing how the system works on real samples, and the range of system targets was also expanded. The work was published in 2022 in the ACS journal *Analytical Chemistry* and was chosen from among 64 ACS journal articles to receive the 2022 ACS Editor's Choice Award.

The OCEANS project was developed in part through a critical collaboration with NASA's Goddard Space Flight Center, where the liquid separation science of OCEANS was coupled with flight mass spectrometry. OCEANS has been funded through various NASA sources, including the Instrument Concepts for Europa Exploration (ICEE)-2 and Maturation of Instruments for Solar System Exploration (MatISSE) programs, as well as JPL funding through the JNEXT program. Most recently, MatISSE funding was jointly awarded to the MDL and Goddard teams to bring OCEANS and the entire European Molecular Indicators of Life Investigation (EMILI) suite to TRL 6, the next step on the journey to looking for signs of life beyond Earth.

OCEANS also has applications closer to home. The system is currently being modified so that it can be used on the International Space Station to ensure that astronauts' drinking water is free from contamination. Additionally, OCEANS could be further tailored for use on Earth, including monitoring harmful algal blooms, supporting precision agriculture, and conducting broad surveys of the planet's changing environment. On Earth or in space, OCEANS is a potentially game-changing system that will help better understand Earth and the solar system.



Mass spectrometry data acquired on amino acids detected in a sample from Mono Lake, California



A Novel and Sensitive Method for the Analysis of Fatty Acid Biosignatures by Capillary Electrophoresis-Mass Spectrometry, Analytical Chemistry, 2022

LEAD
LEADING THE WAY

MDL was founded to lead: its creation was initially proposed in response to a letter asking about which areas JPL could take the lead in for NASA. Since MDL began operations, it has sought to stay at the cutting edge of the microdevices field, conducting R&D to push the boundaries of microfabrication and detector technology, among many other areas. In parallel, it makes strategic investments in infrastructure, hires and supports the brightest minds in the field, and solicits input from experts to help guide future plans. Collectively, they help MDL lead the way with outreach, collaboration, and enabling technologies and devices.

INSPIRATION FOR EVERYONE

MDL's efforts have a substantial, far reaching impact. From supporting prominent global missions that reveal how humans affect the planet to printing millions of names on tiny chips that have gone to space, MDL is inspiring people worldwide to think about our place in the universe.

CARBON PLUME MAPPER

SOURCING EMISSIONS

Carbon Mapper will locate greenhouse gas plumes worldwide

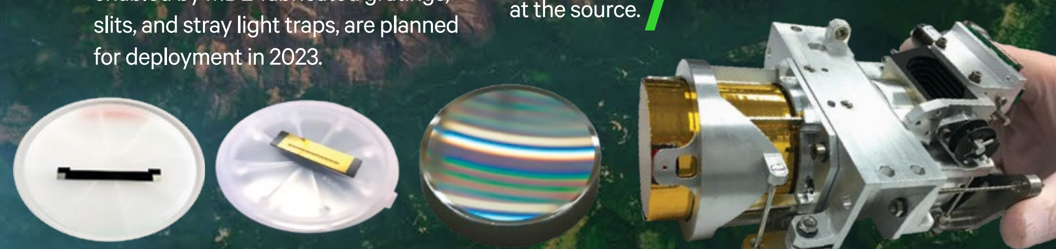
Humanity has less than 10 years left to reach critical milestones that will help mitigate the effects of climate change. An important factor in this fight is understanding where greenhouse gases are emitted and in what quantities. To that end, the nonprofit organization Carbon Mapper has assembled a consortium of experts to develop instruments and technologies that will help pinpoint the locations of greenhouse gas emissions worldwide.

Carbon Mapper's mission will build on previous efforts undertaken by the state of California and JPL to map greenhouse gases at the state level. The instruments in that mission, the California Methane Survey, were deployed on board aircraft and were involved in five campaigns between 2016 and 2018. This new Carbon Mapper mission is a partnership between Carbon Mapper, the state of California, JPL, and several universities and philanthropic organizations. It will take the California Methane Survey to the literal and figurative next level by launching two test satellites containing hyperspectral imagers. These imagers, enabled by MDL-fabricated gratings, slits, and stray light traps, are planned for deployment in 2023.

The test satellites are just the beginning. The ultimate goal for Carbon Mapper is to launch a constellation of satellites that will provide frequent, real-time monitoring of greenhouse gas emissions globally. This monitoring will help achieve three main project goals: accelerating the mitigation of methane super-emitters, independently verifying power plant carbon dioxide emissions globally, and delivering more than 25 additional hyperspectral indicators for carbon and ecosystem management.

As part of this effort, Carbon Mapper is committed to making all of its data freely and publicly available, making it easier to foster accountability, quickly reach conclusions, and rapidly generate action plans. Data are available through a publicly accessible portal, where data visualizations are continuously improved and data sets continue to expand. Eventually, Carbon Mapper's constellation of satellites will provide weekly monitoring of carbon dioxide and methane emissions globally, a critical step in combatting climate change by identifying where emissions come from and enabling mitigating actions to be taken at the source.

KNOWING WHERE GREENHOUSE GASES ARE EMITTED WILL AID IN MITIGATION EFFORTS



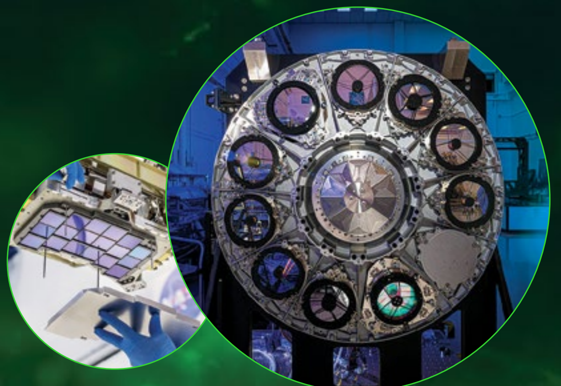
Light trap · Slit · Grating · Prototype spectrometer

MDL'S E-BEAM WRITTEN OUTREACH CHIPS MESSAGES FROM EARTH

MDL provided e-beam-fabricated public outreach signature chips with thousands to millions of names and images to numerous flights.

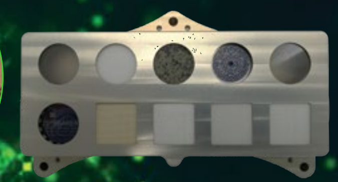
2023 EUROPA CLIPPER

The mission's planned "Message in a Bottle" campaign invites people around the world to sign their names to a poem written by U.S. Poet Laureate Ada Limón. The chip is expected to include more than a million names.



2022 ROMAN SPACE TELESCOPE

The Roman microchip included about 1600 names of people and organizations that contributed to the mission.

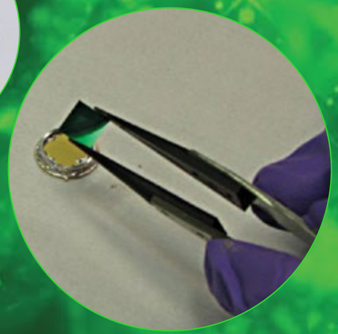


2020 MARS2020 ROVER

The Perseverance Rover carried three small chips with 10.9 million names, along with the essays of the 155 finalists in NASA's "Name the Rover" contest. The "Send Your Name to Mars" outreach campaign won a Webby award for Best Social Community Building and Engagement, as well as the People's Voice Webby. The names were collected in Unicode, which covers most of the written languages in the world.

2018 INSIGHT MARS LANDER

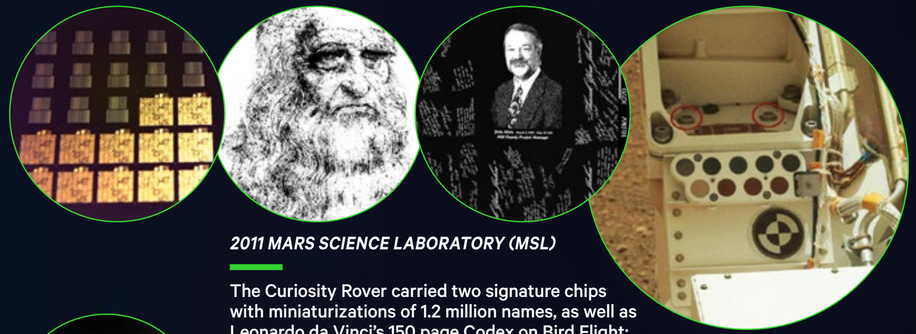
Two microchips with a total of 2.4 million names were affixed to the deck of the lander and are now covered in Martian dust.



2014 ORION SPACECRAFT TEST FLIGHT

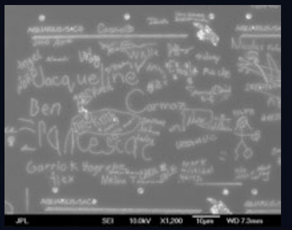
The mission chip contained 1.3 million names. Those names will be included in future Journey to Mars missions.

NASA's public outreach website featured electronic "boarding passes" issued to the public worldwide who signed on to have their names sent into space on the 2014 ORION Spacecraft first test flight and onto the surface of Mars on the Mars 2020 Perseverance Rover.



2011 MARS SCIENCE LABORATORY (MSL)

The Curiosity Rover carried two signature chips with miniaturizations of 1.2 million names, as well as Leonardo da Vinci's 150 page Codex on Bird Flight; Da Vinci's self-portrait; and essays, drawings, and other submissions from finalists and semifinalists who participated in the rover naming contest.

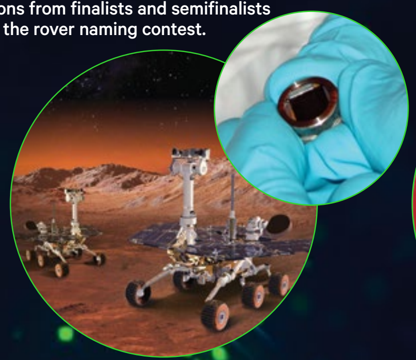


2011 AQUARIUS SAC-D MISSION

MDL took 150 pages of scanned signatures and drawings by the visiting children of Aquarius project team members and wrote them all onto a chip.

2007 DAWN MISSION

The mission to the asteroids Vesta and Ceres included a microchip with more than 360,000 names collected on the Dawn website.



2003 MARS EXPLORATION ROVERS (MERs)

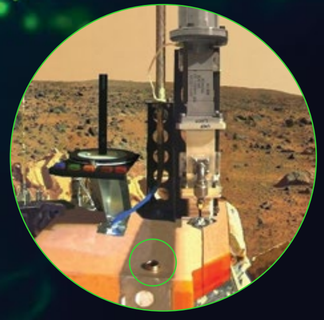
The Spirit and Opportunity rovers each included scanned images of thousands of handwritten signatures from the MER team, visitors to the spacecraft viewing gallery, and schoolchildren from classrooms around the country.

2003 SPITZER SPACE TELESCOPE

Spitzer project team members submitted numerous pages of information that were miniaturized by MDL and placed on the body of the spacecraft.

1999 STARDUST MISSION

The mission carried two chips containing 200,000 names, including names inscribed on the Vietnam Veterans Memorial in Washington, D.C., and grayscale images of the Stardust team.



1996 MARS PATHFINDER LANDER

The Mars Pathfinder lander carried the first signature chip sent to Mars (small round gold button in the center foreground of the image). It contained thousands of miniaturized handwritten signatures from the Pathfinder team; people who visited the Assembly, Test, and Launch Operations (ATLO) viewing gallery; and schoolchildren from classrooms around the country.

1991 SPACE SHUTTLE STS-37

The first e-beam written chip to fly on a mission was an 8-mm-square chip carried on the Atlantis STS-37 Space Shuttle in spring 1991. It contained over 7,600 names, including those of NASA and Caltech senior management and all JPL employees and retirees as of January 1990. Each letter was one micrometer high, which is 100 times smaller than the diameter of a human hair.

NASA SUPPORTS MINORITY-SERVING INSTITUTIONS

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

FLORIDA INTERNATIONAL UNIVERSITY

MDL's collaboration with Florida International University is inspiring the next generation of scientists

In the Plasma Forming Laboratory, high-temperature plasma is sprayed on metallic samples to deposit FIU's coating material.

A year ago, Florida International University (FIU) was considered "a top public university." Since then, however, its prestige has soared: it is now 72nd among American public universities, making it the fastest-rising US university among US News and World Report public university rankings. It has also been ranked among the top 20 public universities contributing to the public good. The inclusion of "International" in its name is indeed justified: it has more than 58,000 students from 142 countries. FIU is also a research university, with 155 of its faculty and postdocs winning many research awards and producing high-quality, peer-reviewed papers.

ACTIVELY ENHANCING THE EDUCATIONAL AND CAREER OPPORTUNITIES OF UNDER-REPRESENTED MINORITIES AND WOMEN

FIU receives NASA support via the Minority Undergraduate and Research Education Program (MUREP), and MDL and JPL have had a significant role in enhancing the quality of the programs at FIU. MDLers and JPLers have directly mentored FIU students, especially engineering students who are underrepresented minorities and/or women. This collaboration helps expose these students to possible careers in NASA, both through examples at FIU and through internships where they can work on real problems at MDL. The program not only gives advantages to the students but also serves as a potential funnel that can direct potential recruits into JPL and MDL. Many of the students are involved in the NASA MUREP Institutional Research Opportunity (MIRO) Center for Research and Education in 2D Optoelectronics (CRE2DO), which has gained a strong reputation by fulfilling its goals to develop technologies and materials for use in space applications.

Schematic drawing of a mid-IR methane mapper mounted on a drone for investigating methane emissions from natural sources such as wetlands and permafrost. The mapper uses an interband cascade laser (ICL) to emit light near 3.27 μm and a mercury-cadmium-telluride (MCT) detector.

EXPOSING UNDERREPRESENTED MINORITY STEM STUDENTS TO AN EARLY CAREER PATHWAY IN NASA-RELATED EARTH AND SPACE SCIENCE RESEARCH

HOWARD UNIVERSITY

Howard University in Washington, DC, was founded in 1867 and is a private, federally chartered historically Black research university

Currently, its intake is 67% Black, but it has 84% minority enrollment overall. Its proud claim to inclusivity is, "Our community of more than 12,000 undergraduate, graduate and professional students represents 53 states and territories, and 53 nations." It is a prestigious school: Howard is considered a Black Ivy League institution and has an acceptance rate of only 35%. It ranks first in the US for producing minority doctoral graduates in computer science. It offers a wide range of academic programs, including in natural sciences, life sciences, and engineering and technology.

MDL collaborates with Howard University professor Christopher Boxe, an expert in air quality models and data processing algorithms. Professor Boxe has developed models for the environmental monitoring and assessment of water, air, and soil on Earth and Mars. Through this collaboration, methane measurements from a mid-IR lidar that is sensitive to background levels are being investigated, and there is a special interest in the data processing, visualization and integration of air quality models. Howard also possesses a 31-meter instrument tower, and the collaboration between MDL and Howard enables opportunities for testing novel concepts in this realistic operating platform.

2023 MDL Summer Interns

MDL SETS AN EXAMPLE

MDL's development of technology for airborne and spaceborne missions is a long-term process that requires having the right people, having the right people advise it, and being equipped with the right resources. To that end, MDL is always seeking the brightest minds to support the development of cutting-edge microdevice innovations. These individuals can arrive at MDL as undergraduate or graduate student interns. Some continue their association with MDL. Others become postdocs through the NASA Postdoctoral Program, the JPL NEXT program, or other programs. All are provided with the training needed to support the next stage in their careers. They are also provided with the resources they need through continual and strategic investment in MDL's facilities. Helping to guide these investments in people and infrastructure is MDL's Visiting Committee, a group of experts that convenes every two years to provide input that informs long-term planning.

MDL INVESTS IN THE FUTURE


Hani Nejadriahi

Dr. Nejadriahi received her PhD in photonics from the University of California, San Diego (UCSD), where she developed a hybrid platform: silicon-rich silicon nitride using plasma-enhanced chemical vapor deposition (PECVD) with a refractive index and thermo-optic coefficient close to that of silicon. Using this platform, Dr. Nejadriahi fabricated and characterized an all optical phased array system on a chip. This system is useful for beam steering and light detection and ranging (lidar).

At MDL, Dr. Nejadriahi's research focuses on developing ultra-low-loss photonic integrated circuits (PICs) in stoichiometric silicon nitride and gallium nitride. Silicon nitride plays a crucial role in laser optics systems for cold atom sensors and applications, while gallium nitride is a well-established compound semiconductor with many advantages and applications.

As part of her efforts to improve laser optics and miniaturize cold atom sensors, Dr. Nejadriahi has focused on developing ultra-narrow-linewidth external cavity lasers around 780-852 nm; commercial lasers are either not available at these wavelengths or do not have a sufficiently narrow linewidth. This technology will be important in many applications that would benefit from integrated narrow-linewidth lasers.

MDL IS SUPPORTING THE NEXT GENERATION OF RESEARCHERS

Additionally, to build a fully working system on a chip, Dr. Nejadriahi is developing more devices, such as wavemeters, phase modulator/switches, and isolators, as well as passive components such as splitters, couplers and interferometers.

Dr. Nejadriahi is actively is working in the Advanced Component Technology (ACT) program, where she designs, fabricates, and characterizes acousto-optic devices in GaN-on-sapphire to achieve high-performance acousto-optic modulators (AOMs) with mW-level drive power. These waveguide platforms will enable low SWaP (Size, Weight and Power) and help produce a new generation of reliable devices and systems that will be useful in many NASA applications, from Earth science (cold atom sensors) to astrophotonics (coronagraphs, wavefront correction, and spectrographs).

These PICs can operate at any wavelength depending on the bandgap of the material they are designed in. They represent fertile ground to explore new types of flight-compatible systems.

In addition to integrated photonics, Dr. Nejadriahi works with Dr. Dan Wilson on the design and fabrication of diffractive optical elements using both binary and grayscale lithography (gratings for spectrometers, lenses, etc.). Many of these components are essential for MDL flight projects.

Dr. Faramarzi joined MDL as a NASA Postdoctoral Program (NPP) Fellow in February 2023. His research is focused on developing quantum-limited parametric amplifiers using superconducting materials with nonlinear kinetic inductance. This technology was pioneered at MDL ten years ago by Dr. Faramarzi's NPP supervisor, Dr. Peter Day, and his team.

Dr. Faramarzi has been characterizing the performance of the newest generation of these amplifiers, which are designed for frequency bands from VHF to Ka, by taking gain and noise measurements at base temperatures below 30 mK. Parametric amplifiers are fabricated at MDL's fabrication facility by one of his mentors, Dr. Henry Leduc. Most superconducting thin films used for parametric amplifiers at MDL are NbTiN and TiN due to their high kinetic inductance and their nonlinear response to applied DC and AC power.

During his NPP fellowship, Dr. Faramarzi's primary objective is to push parametric amplifier technology to the millimeter and sub-millimeter frequencies. Kinetic inductance traveling wave parametric amplifiers (KI-TWPAs) in these frequency bands can be an alternative to superconducting-insulating-superconducting (SIS) mixers due to their larger fractional bandwidth and quantum-limited performance. These advantages can be leveraged to improve receiver sensitivity, and it would be a simple and relatively low-cost way to enhance the scientific value of any instrument employing heterodyne receivers.

Dr. da Costa received his PhD in electrical engineering from the University of Alcala, Spain, in 2020. During that time, he was also an early-stage researcher for the European Research Council "ITN-FINESSE," which led to predoctoral research at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. During his graduate studies, he developed new optical techniques for optical fiber distributed sensing and optical fiber characterization, and he was part of an engineering team for a lab spinoff (FOCUS-Tech) that developed a distributed acoustic sensing instrument that is now licensed to Aragon Photonics as the High-fidelity Distributed Acoustic Sensor (HDAS). He also worked briefly as a research and development engineer for HBK FiberSensing, Portugal, and EQS Global, Portugal, developing sensing solutions based on fiber Bragg grating technology.

During his postdoctoral research at Caltech, Dr. da Costa continued developing new optical fiber sensing techniques aimed at planetary seismology, studied nonlinear optical techniques for sensing and spectroscopy, and developed new integrated optical sources in thin-film lithium niobate with the Nonlinear Photonics Group.

Farzad Faramarzi

Luis da Costa

Dr. da Costa joined MDL in November 2022, and his research focuses on coronagraphs. Coronagraphs conventionally require bulky free-space optic setups, but Dr. da Costa's research leverages new developments in application-specific photonic computing architectures to perform coronagraph operations on an integrated platform. These operations can be performed using some general-purpose computing architectures, such as interferometer meshes, which enable encoding linear operations on a chip by simply tuning a set of phase shifters. This setup enables light from a star to be routed to one of the chip's outputs and light from surrounding objects to be routed to the remaining outputs.

The current state of the art enables a selective switch of single-wavelength light (1550 nm) with a more than 70 dB extinction ratio between outputs (or, more generally, to synthesize any possible output) from a single input to the chip. Challenges include generalizing this result to arbitrary inputs, improving losses in coupling to and from the photonic chip, improving the stability and control algorithms required to keep starlight well separated from exoplanetary light, and improving the bandwidth of this operation.

MDL Postdocs

Dr. Bianconi joined MDL in early 2022 as an MDL Next postdoctoral fellow. Since then, he has focused on light detection and ranging (lidar), which is the optical equivalent of radar. Lidar is an incredibly powerful tool for investigating the atmospheres of Earth and other planets, and it is expected to play a key role in advancing the understanding of climate and extreme atmospheric events. Unfortunately, current lidar instruments require complex and bulky components, precluding their successful deployment on a large scale and hence limiting their impact.

Dr. Bianconi's focus has been on leveraging modern semiconductor laser technology to fabricate compact, energy-efficient lidar components and subsystems that can be easily used in large-scale airborne and spaceborne deployments. Such lidar instruments can be used on platforms with strict SWaP (Size, Weight and Power) constraints, such as CubeSats or unmanned aerial vehicles (UAVs). On these platforms, these instruments could unlock novel and disruptive applications of lidar-based atmospheric sensing and significantly increase lidar coverage of Earth.

For example, in collaboration with Harvard, Dr. Bianconi designed a lidar instrument that could be deployed on a solar-powered stratospheric aircraft that could operate autonomously and globally for up to five months and map the amount of precipitable water vapor held in the atmosphere; this information is useful for predicting and monitoring extreme weather events.

Another interesting application is in monitoring the emission of methane, which represents a small fraction of Earth's atmosphere but has an outsized effect on climate change, as it is believed to be responsible for about one-sixth of current global warming. Miniaturized lidar instruments based on semiconductor interband cascade lasers developed at MDL can map methane concentrations with unprecedented sensitivity in the 1-100 m range.

Simone Bianconi

These instruments can be deployed on small drones to autonomously survey areas of suspected natural methane emissions, complementing and validating the coarse methane concentration maps produced with sophisticated spaceborne and airborne NASA instruments like the Earth Surface Mineral Dust Investigation (EMIT) and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), respectively.

The theoretical and experimental framework developed by Dr. Bianconi has demonstrated that semiconductor lasers used in a continuous wave can match the performance of current state-of-the-art pulsed solid-state lasers while drastically improving their size and energy efficiency. Another advantage of semiconductor laser technology is that it can leverage integrated photonics to transfer on-chip some of the functionalities currently performed by bulk optics and electronics, such as frequency control and stabilization, thereby drastically reducing the size and improving the reliability of lidar instruments. This novel and disruptive approach to lidar has the potential to expand the applicability and impact of spaceborne and airborne lidar in daily life.

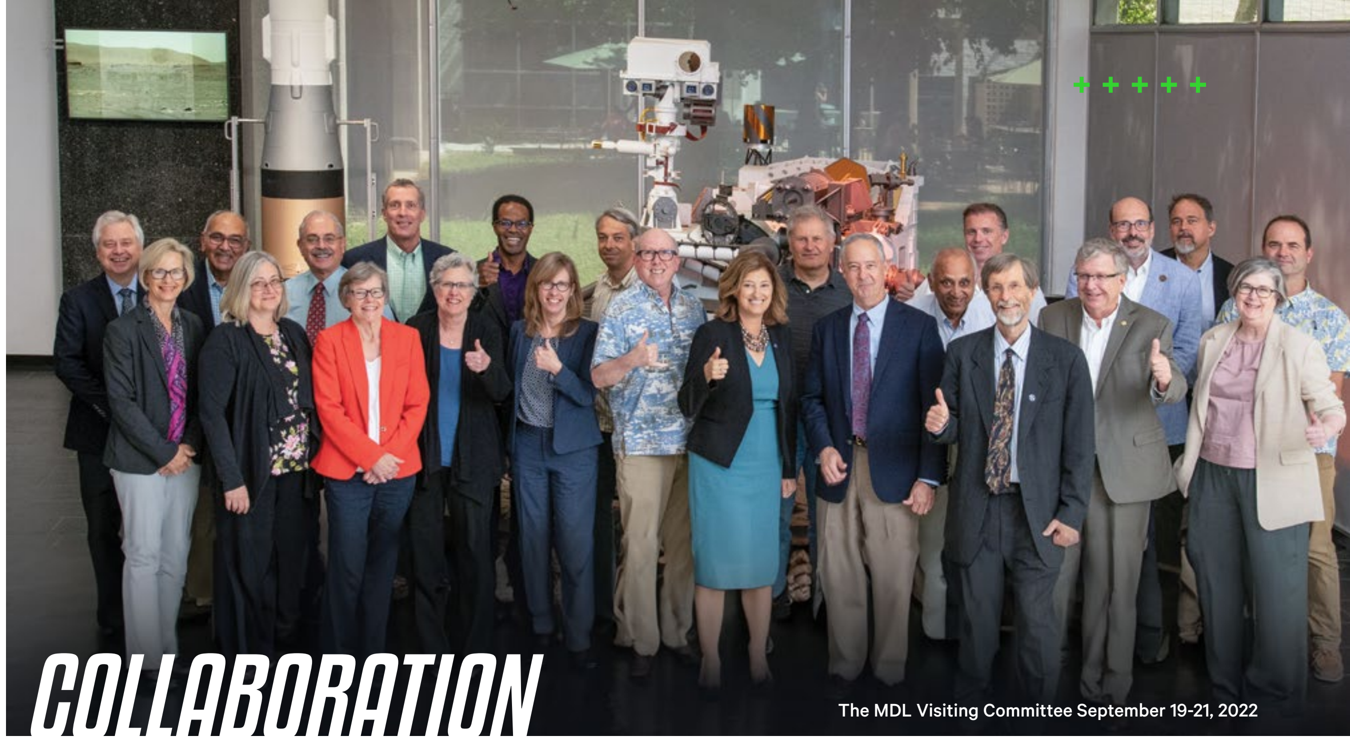
INTEGRAL SUPPORT: HOW THE BUSINESS TEAM DRIVES MDL'S SUCCESS

MDL OPERATIONS RELY ON MORE THAN JUST SCIENCE AND ENGINEERING

Those needs are met through the often-unseen efforts of the Business Administration Manager and MDL's team of administrators. The Business team supports MDL activities with their constantly updated knowledge of and experience with JPL processes, policies and business tools. They work within very broadly defined areas and are essential to maintaining MDL policies and procedures.

The team supports MDL management by identifying and analyzing complex workforce and budgetary issues and then recommending solutions and strategies that promote the most effective ways of working. All at MDL appreciate the Business team, who make it look easy to keep MDL running smoothly.

MDL Business Administration Team: (Left to Right)Trophie Roberts, Katie Redfield, Rebecca Prompichai, and Richard Castillo.



COLLABORATION

The MDL Visiting Committee September 19-21, 2022

JPL AND MDL SCIENTISTS AND TECHNOLOGISTS EXCHANGE IDEAS AND THEREBY IMPROVE EACH OTHER

In an ideal world, scientists and technologists would share their ideas and challenges with one another, leading to a self-sustaining virtuous cycle of asking questions, presenting the most challenging problems, and inventing the technologies or innovating new strategies to address them.

Life at JPL and MDL comes very close to this idealized representation, but leadership recognized the value of additional, structured dialogue. Consequently, the senior management of MDL and the JPL Science Division organized an "Idea Exchange" workshop in October 2022 with support from JPL's Chief Scientist and Chief Technologist.

The objective of the workshop was to explore new areas of collaboration and encourage future partnerships. It consisted of short (10 – 15 minute) presentations from the Science Division and MDL staff members, followed by breakout sessions to discuss areas of mutual interest and identify potential future research opportunities.

The Office of the Chief Scientist and Chief Technologist encouraged any teams involved in new partnerships arising from the workshop to submit proposals to an internal JPL program that could make awards within that current fiscal year. The event was such a success that additional workshops with specific focuses are planned for 2023.

EXPERT EXTERNAL GUIDANCE

However hard one tries, from the inside of an organization, it is very difficult to detach and view that institution objectively. To help obtain expert, objective input on MDL's future, in 2007, Dr. Jonas Zmuidzinas, then the MDL Director, established an MDL Visiting Committee. The Committee includes a broad spectrum of highly talented and accomplished individuals external to MDL. They convene every two years, visit MDL, review its activities, and produce a report.

Their insights are often unexpected, but they are all taken very seriously and are frequently implemented in MDL's future.

MDL Support Team [left to right]: Mark Mandel, James Lamb, Anthony Loveland, John Liu, James Wishard (front), Bamdad Mesri (rear), Ramzy Rizkallah (rear right), Amy Posner, Chuck Manning, Michael Martinez, Efren Estrada, Frank Greer, Toney Davis.

KEEPING MDL AT THE CUTTING EDGE

MDL collaborations provide critical deliveries for NASA and other agencies around the world, and they are enabled by sustained strategic investments in equipment, infrastructure, and personnel. MDL was constructed in the late 1980s to enable new space observables for NASA and the world. In the subsequent three decades, the scientists and engineers at MDL have invented, produced, and delivered unique microdevices and components for instruments serving the space missions of the world's largest agencies, including NASA, the European Space Agency (ESA), the Indian Space Research Organization (ISRO), the Japanese Aerospace Exploration Agency (JAXA), and Roscosmos, to name a few.

These microdevices often uniquely enable critical science ranging from studying the universe from the present (star formation) to the far past (cosmic microwave background from the Big Bang), from mineralogy on Earth and Mars to life detection in the oceans of the outer planet moons, and from forest fires to methane plumes from super-emitters on Earth. Past, current, and future US missions such as the Curiosity Mars rover (MBE-grown lasers and packaging for the Tunable Laser Spectrometer instrument), the James Webb Space Telescope (e-beam-fabricated occulting spots), the Earth Mineral Source Dust Investigation (e-beam-fabricated mirror, gratings, and black silicon slit), the Nancy Grace Roman Telescope (e-beam-fabricated occulting spots and black silicon masks, lithographically patterned metallization for deformable mirrors, and packaging support for the Coronagraph Instrument) and life detection instruments (under the Outer Water Planet Life Detection Systems [OWLS] program and the Mars Organic and Oxidant Detectors for the Urey instrument) have all critically benefited from uniquely enabling MDL technologies. MDL technology developments have also aided the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) instrument on NASA's Mars Phoenix lander, and the ESA's microseismometer instrument on NASA's Mars Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission. The ESA, JAXA, ISRO, and Roscosmos have utilized detectors and optical components such as superconducting spiderweb bolometers (ESA's Herschel and Planck Space Observatories), transition edge superconducting bolometer-based spectrographs (Background-Limited Infrared-Submillimeter Spectrograph [BLISS] for the Japanese SPICA mission), diffractive optics (ISRO's Moon Mineralogy Mapper instrument on the Chandrayan-1 Lunar Orbiter), and delivery of the Mars Oxidant Experiment (MOx) for the study of oxidizing agents in the Martian soil and on Roscosmos' Mars '96 lander.

MDL EQUIPMENT IS FREQUENTLY REFRESHED, AND NOW THE MDL FACILITIES SYSTEMS ARE BEING MODERNIZED

This established track record has been achieved thanks in large part to sustained JPL investment in MDL's infrastructure, primarily focused on the modernization of MDL's semiconductor equipment complement. This investment has been extremely successful and has resulted in the renewal or replacement of over 25% of the MDL-installed base over the last 5 years. Some recent examples of new equipment include a new SPTS Rapier deep reactive ion etcher for silicon processing, two Heidelberg MLA-150 direct-write maskless lithography tools, an EV 520 wafer bonder, and an EcoClean photoresist stripper, to name a few.

However, despite this continuous institutional support, MDL's facilities systems have not been a part of a sustained modernization effort and now need attention. Many of these key pieces of support equipment have been in continuous operation since the building was originally constructed in the late 1980s and now require renewal or replacement. To address these needs, a special MDL facilities initiative was launched in late 2020 to identify and proactively address facilities systems feeding the MDL cleanroom that were at or near their projected end of life. The analysis included anything affecting semiconductor processing, including HVAC and air handling, compressed air, cooling water, the house vacuum, and deionized (DI) water.

NASA AND SPACE AGENCIES AROUND THE WORLD HAVE BENEFITED FROM CONTINUOUS JPL INVESTMENT IN MDL

The first support system to be renewed in this initiative was the concrete vibration isolation pads anchoring the mutually redundant inorganic exhaust blowers. One of these pads was poured and anchored in late 2021 and brought into full service in mid-2023. Other examples of facilities modernization and renewals include gowning room upgrades, a facility remote monitoring system with over 200 points, DI and process cooling water system upgrades, incipient fire detection system replacements, and liquid leak detection capabilities. The future of MDL is now being reviewed carefully to strategically plan for the future, with an eye towards MDL at the 50-year point of operation. A complete report detailing these plans will be released in 2023.

MDL's operations and infrastructure are sustained and enabled by the Central Processing and MDL Support Group, which is led by Technical Group Supervisor and MDL (Operations) Manager Frank Greer. The 13 dedicated professionals who make up this group not only bring technical expertise to their own specialties but also work as a team, augmenting each other's skill sets and offering processing expertise and capabilities to others. With a consistent focus on continuous improvement, the group's responsibilities include configuration control, facilities and safety oversight, maintenance, process development, project support, and new equipment specification and installation.

LEAD

LOOKING TO THE FUTURE

MDL is never static. Its strategic plan is updated regularly, fostering the constant renewal of itself and its view of the future. MDL's vision is informed by NASA's Decadal Surveys, input from the Visiting Committee, and the expertise and imaginations of MDL engineers and scientists.

MDL is a strategic investment for JPL because the technologies it develops and the expertise and capabilities it houses often provide JPL with a competitive advantage in winning proposals and obtaining greater science returns from NASA missions. Due to the investments made in its capabilities over the last three decades, MDL attracts and retains high-level talent who can advance its technologies and build on its existing foundations. New, game-changing technology advances are often proposed through internal funding opportunities and are then incorporated into MDL's portfolio through both its new and existing staff. While these activities spur new growth in unanticipated areas, equally important are the developments that occur through the optimization of equipment and the processes used for current deliverables.

NASA regularly commissions the National Academies to produce a prioritized 10-year forward look for various scientific areas. These Decadal Surveys are NASA's principal guidance on scientific and budgetary priorities. MDL aligns with NASA's Decadal Surveys in setting its technology development foci. MDL hopes to contribute to missions, develop future technologies, and influence specific requirements by publicizing its capabilities and technology developments for the scientific community.

MDL'S RESPONSES TO NASA'S DECADAL SURVEYS

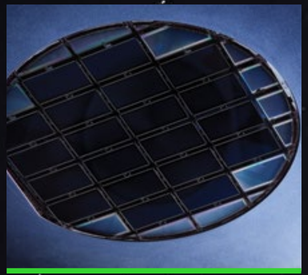
MDL develops its long-term strategies based on the needs of future NASA missions, especially as outlined in the Decadal Surveys. MDL currently plans to contribute to multiple missions aligned with the Decadal Surveys

Large (6-meter) IR/optical/UV observatory (~2030) {and possible MDL developed and supplied UV/Vis/NIR, MidIR, far IR detectors; Diffractive optic gratings, cryogenic packaging; mirror control; and smaller SWaP optical components.}

Medium-scale probe missions (~2025-2035) in the Far-IR complementing the European Space Agency's (ESA's) Athena X-ray mission. {Includes possible missions (e.g. PRIMA, etc.) with MDL developed and supplied detectors and components — MKIDs, QCDs, and THZ; MgB2, cyrogenic packaging; and Optical Com.}

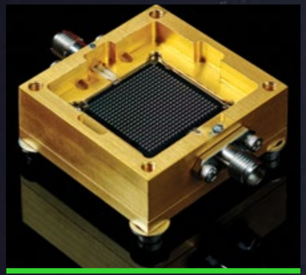
Roman Space Telescope Cronograph Instrument (CGI) (2027 launch) {with MDL supplied Diffractive Optics and occulting spots, light trapping surfaces, precision slits, mirror control actuator elements, coatings, etc.}

Far-IR observatory (~2025) {and MDL-fabricated quantum capacitance detectors and large-format superconducting kinetic inductance detectors [KIDs]}



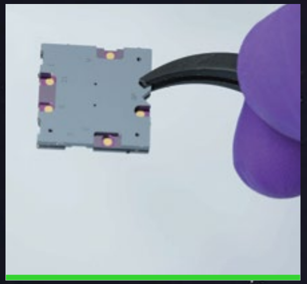
UV flagship mission (2030 start) {and delta-doped charge-coupled devices [CCDs] for detection in the UV, as well as atomic layer deposition [ALD] protective mirror coatings}

Solar System Exploration Survey (2023-2032), including Mars sample return equipment {with MDL supported camera systems}, Uranus orbiter probe flagship, Enceladus orbiter/lander flagship {involving life detection instrumentation systems for ocean worlds} {and possible inclusion of MDL supported optical com in all}

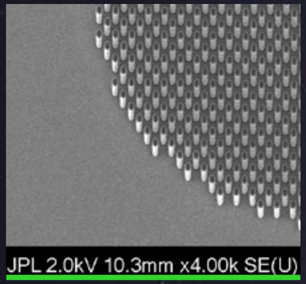


Earth science needs for environmental monitoring {including MDL detectors in the IR and far-IR (THz), specific semiconductor lasers and integrated sub-systems for absorption lines for specific atmospheric gases, and multiple enhancements to spectrometers with optical enhancements that improve precision and reduce size}

Optical communications for enhanced data rates in deep space, i.e., Deep Space Optical Communications {including MDL developed superconducting nanowire single photon detectors [SNSPDs]}



Reduced size, mass, and power in spacecraft environmental monitoring {involving MDL developed high-pressure microelectromechanical systems [MEMS] microvalves, semiconductor lasers and associated systems}



Reduced size in integrated optical systems {involving MDL developed metasurfaces and electromagnetic wave manipulation}

SUPPORTING NASA INTO THE FUTURE

HOMEGROWN INNOVATION FUELS TECHNOLOGY PROGRESS

MDL RESEARCH PROJECTS

MDL staff can compete for internal JPL funding to explore and develop new ideas, thereby reducing risk in future proposals. Progress on some of these preliminary projects is highlighted in the "Technology Progresss" topical section that follows. These projects have various objectives ranging from transformative changes to manufacturing processes, from new technologies for components and instruments to the components and instruments themselves, and from new ways of observing phenomena to new strategies for interpreting data. Many of these projects are high risk and high reward, but when they succeed, they lead to completely new technology for NASA missions.

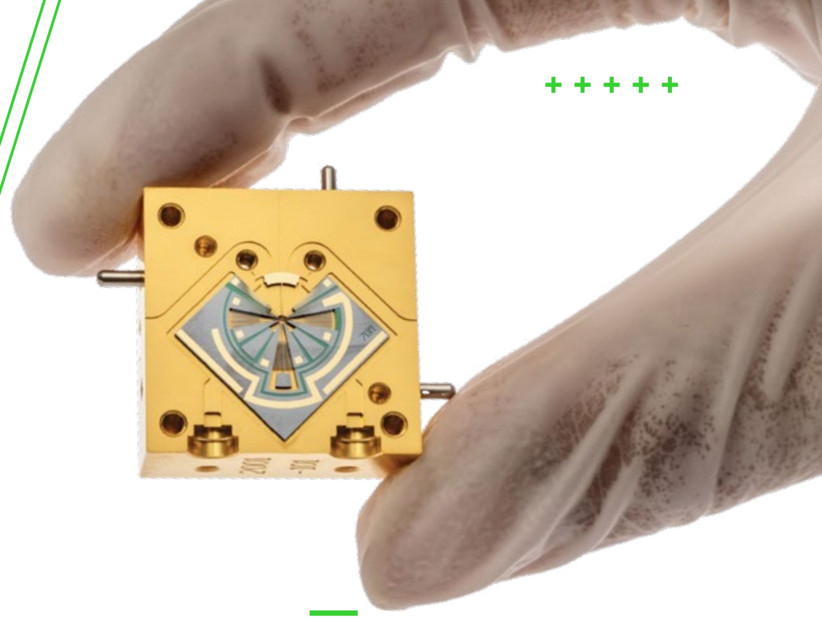
MDL INNOVATION AND INVENTION CONTINUE TO SEED FUTURE SUCCESSES

PROGRESS

CONTINUOUS IMPROVEMENT

MDL's work goes far beyond the missions and mature technologies that make headlines. To support a culture of continuous improvement, MDL scientists also work on disruptive technologies that are still being developed. Just a few are highlighted next.

NASA's planned Europa Mission is designed to provide unprecedented insight into the icy moon's capacity to support life.



Photograph of the fabricated MEMS switch mounted into the milled brass waveguide block for measurements.

CONTACTLESS CALIBRATION

A NEW SWITCH TECHNOLOGY WILL ENABLE SMALLER DEVICES WITH LOWER POWER REQUIREMENTS

When exploring comets, icy moons, and other objects beyond the reach of traditional optical telescopes, scientists rely on advanced spectroscopy. Some of the best results come from the analysis of high-frequency radar signals using radar molecular spectrometers. These specialized instruments are highly sensitive to water, which is of great interest to researchers due to water's critical role in biology and geology. The system that supplies data to the spectrometer must be frequently calibrated to ensure accurate measurements. Traditionally, this calibration has been achieved using a flip mirror, a mechanical piece facing either the antenna or a known signal load. However, these mirror-activation systems are bulky, power hungry, and prone to mechanical failure, traits that are far from ideal for a spacecraft operating in cold, distant environments. Subsequent micromechanical switching systems are smaller and require less power, but their reliance on mechanical electrical contacts means they are still prone to failure.

To address this problem, MDL has received internal Research & Technology Development (R&TD) funds to develop a contactless rotating MEMS waveguide switch that can continuously calibrate the antenna system to detect H_2O and HDO water lines at 557 GHz and 600 GHz. By using electromagnetic bandgap (EBG) structures in the form of pins, the electromagnetic wave can be isolated between ports without the need for mechanical or ohmic contact between states. By rotating the switch via electrostatic activation, the receiver can be connected to either the calibrating load or the antenna, resulting in reduced size, a lower power draw, and a greatly enhanced reliability.

The switch was microfabricated from Silicon-on-Insulator (SOI) wafers that were coated with gold to enable its electromagnetic properties.

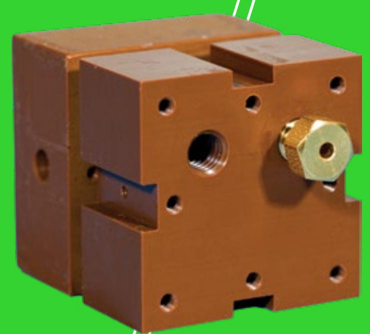
The MEMS switch was then mounted in a waveguide block to test its switching capabilities between the waveguide ports. Testing the device showed that it could rotate up to +/-5 degrees, when only +/- 4.5 degrees is needed for the switching effect, with a voltage of +/- 60 V. The next step will be to integrate the MEMS rotating switch with the rest of the 500-600 GHz receiver for a full system demonstration. This switch was developed in a collaboration between two groups within MDL. It will allow instruments to better operate in remote, hostile environments, greatly enhancing the quality of data received and expanding our understanding of the distant solar system and beyond.

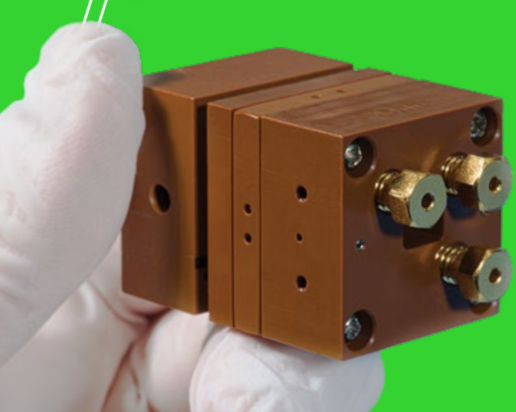
AN MDL-DEVELOPED CONTACTLESS SWITCH WILL HELP LOOK FOR WATER IN DISTANT ICY OBJECTS

THz MEMS switches for instrument calibration

BUT FIRST, CONCENTRATE!

The MEMS preconcentrator is tiny but can detect gases at the parts per billion level

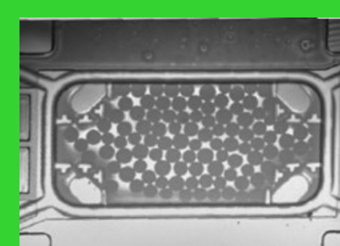




For the Spacecraft Atmosphere Monitor (S.A.M.) to work, gas samples on board the International Space Station (ISS) must be concentrated before they are analyzed. The MEMS preconcentrator (PC) accomplishes this function by capturing hydrocarbons in spherical carbon adsorbents – Carboxen 1000™. The hydrocarbon is released from the adsorbents upon heating and is then injected into the GC for analysis. The PC is effective because it uses very-high-surface-area materials to adsorb as many compounds as possible in a fixed volume, and it can rapidly heat and cool a sample to desorb (release) the material, which enables very-low-concentration compounds to be analyzed discreetly.

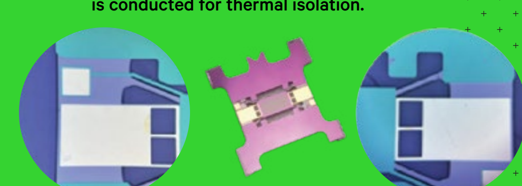
These key features mean that the PC can be reduced to a very small size: 14 x 14 x 0.9 mm^3. Although its volume is less than 1.4 microliters, it can collect enough gas to enable parts per billion (ppb) sensitivity in the system. This extraordinary sensitivity in such a tiny package means that the PC is a smaller payload with smaller power requirements and therefore can be used on many different NASA missions.

The PC will be deployed on the S.A.M. to detect toxins in the cabin air of the ISS, but it also has applications both closer to and farther away from Earth. For example, on Earth, the PC could be used to search for chemical warfare agents and explosives as part of national defense. It could also play a significant role in environmental monitoring, such as analyzing the air for pollution, toxins, and natural gas leaks. In medicine, it could be analyzing patients' breath for early signs of disease. Farther from home, the PC could be used on missions to explore distant planets. The PC is manufactured solely at MDL using its state-of-the-art fabrication facility. A new iteration will be included in the S.A.M. that is scheduled for launch to the ISS in November 2023.



An IR image of the S.A.M. PC looking at Carboxen 1000™ particles packed uniformly and thoroughly underneath the PC heater.

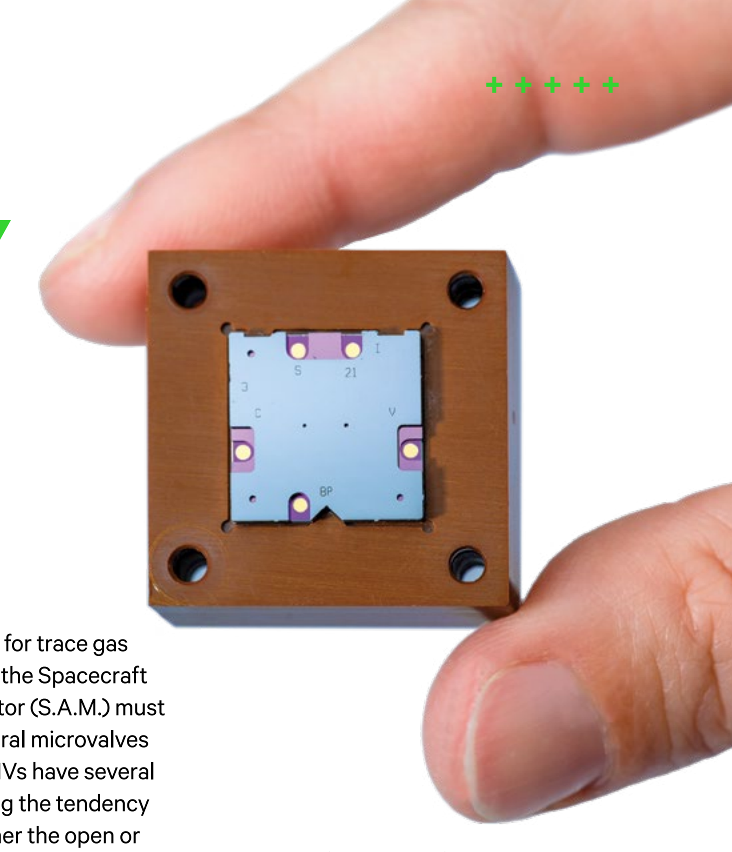
The S.A.M. PC heater zoomed in left and right sides where through etching is conducted for thermal isolation.



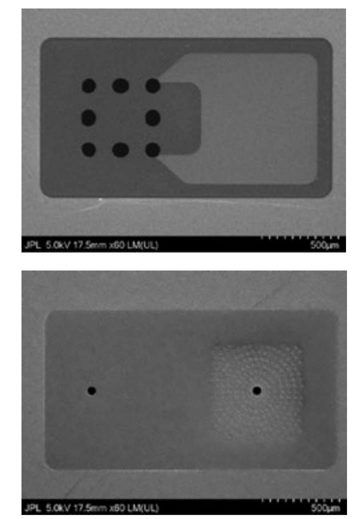
THE PRECONCENTRATOR IS A KEY COMPONENT OF THE SPACECRAFT ATMOSPHERE MONITOR

GETTING UNSTUCK

A new MEMS microvalve is a critical component of the Spacecraft Atmosphere Monitor



An image of a microvalve fabricated at MDL



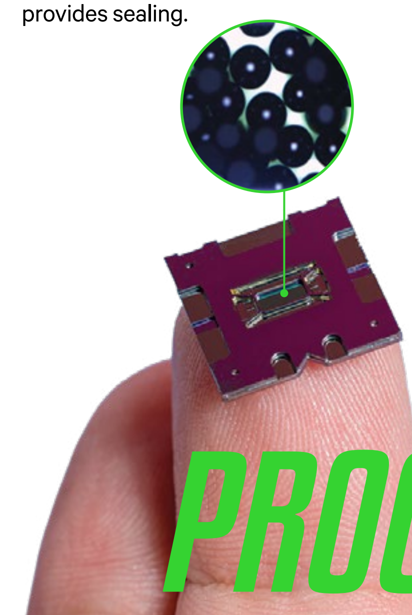
Scanning acoustic microscope images of the membrane and the stationary plate.

The samples used for trace gas analysis (TGA) on the Spacecraft Atmosphere Monitor (S.A.M.) must pass through several microvalves (MVs), but older MVs have several problems, including the tendency to get stuck in either the open or closed position. To address these problems, MDL researchers have fabricated a new MEMS gas MV.

This MV is an electrostatic parallel plate actuator with five independent membranes, all electrically isolated from one another, to fully control the gas flow going to each port and suppress crosstalk. The membranes are fabricated on a Silicon-on-Isolator (SOI) wafer, and a stationary plate hosting the gas inlets and outlets is implemented on a separate SOI wafer. Both are highly doped. Two additional regular silicon wafers complete the valve: the top wafer holds the gas channels and the bottom wafer provides sealing.

All four wafers are bonded via gold-to-gold thermocompression, where the initial gap between the membrane and the stationary plate is defined by adjusting the thickness of the gold layers.

Through methodical simulations for flow and electrostatics using COMSOL software, along with fabrication and testing cycles, MDL has now developed a robust MEMS gas MV that meets key system requirements for the S.A.M.'s operation on the ISS. It has been assembled with the rest of the MEMS components, which have also been developed at MDL: the preconcentrator (PC) and a miniature GC. This MEMS-in-a-block (MIB) is currently being integrated with the rest of the S.A.M. instrument for calibration and testing in preparation for launch to the International Space Station (ISS) in November 2023.

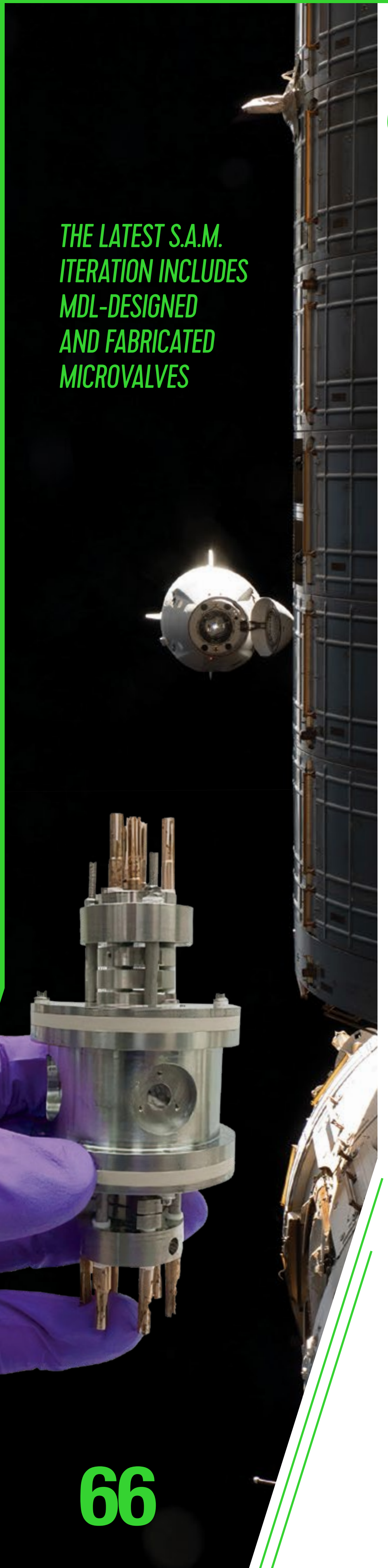


An assembled PC with the carboxen layer; an inset image shows Carboxen™–1000 particles packed inside the PC.

LAUNCH TO THE ISS ON THE S.A.M. IS SCHEDULED FOR NOVEMBER 2023

PROGRESS

S.A.M. BREATHE EASY



THE LATEST S.A.M. ITERATION INCLUDES MDL-DESIGNED AND FABRICATED MICROVALVES

Perhaps nowhere is it more critical to monitor air quality than on the International Space Station (ISS). From August 2019 to July 2021, this function was successfully performed by the first technology demonstration unit (TDU1) of the Spacecraft Atmosphere Monitor (S.A.M.), which returned to JPL in January 2022. During the S.A.M. mission, high levels of benzene were detected on the ISS, so TDU1 was reconfigured while onboard the station and subsequently determined that there was no benzene in the cabin atmosphere; instead, the existing ISS contaminant monitor was giving erroneous readings. For its acting as part of a Tiger Team in supporting this reconfiguration process, the JPL TDU1 team was given a 2022 NASA Honor Award. The mission was so successful that the NASA Advanced Explorations Systems (AES) directorate has funded JPL to refurbish, upgrade, refly, and operate TDU1 on the ISS; it will launch back to the space station in 2024.

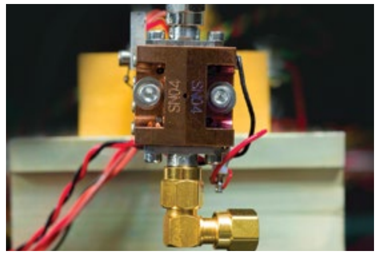
TDU1's high-quality major constituents data and flexible operation have led to the ISS Vehicle Office advocating for two S.A.M. units to operate aboard the ISS for the remainder of the space station's lifetime. Therefore, an updated technology demonstration unit, TDU2, will launch to the ISS in 2023 and continuously monitor the major atmospheric constituents. When commanded, it will analyze the cabin atmosphere for trace volatile organic compounds (VOCs). TDU2 uses the same quadrupole ion trap mass spectrometer (QITMS) sensor as TDU1, but it also includes a MEMS preconcentrator, gas chromatograph, and MDL-enabled microvalve system. Its miniature, ruggedized form factor allows the S.A.M. to be aisle-deployed to monitor the cabin in different locations and during activities such as exercise and sleep.

AES has also funded JPL to build two additional ground-only S.A.M. units that will be used in NASA environmental ground tests and demonstrated to interested commercial companies, bringing this MDL-enabled technology to monitor air quality from space back down to Earth.

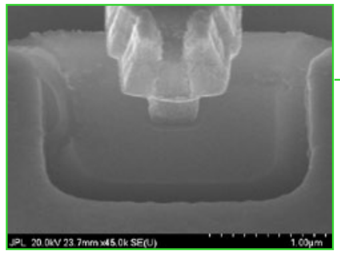
Above: Photographs of the S.A.M. TDU1 (left) at JPL on Feb. 20, 2022 after two years of continuous operation on the ISS, and TDU2 (right), which will fly to the ISS in 2023. TDU2 is currently in final validation testing and is scheduled for launch aboard SpaceX-29 to the ISS. The TDU aluminum chassis is 9.5" x 8.75" x 7.5" in volume with a mass of 9.5 kg. The S.A.M. handles and small form factor allow for the instrument to be easily transported to perform cabin-air monitoring anywhere within the ISS. TDU1 will be upgraded with trace gas analysis (TGA) capabilities and reflown to the ISS in 2024.

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

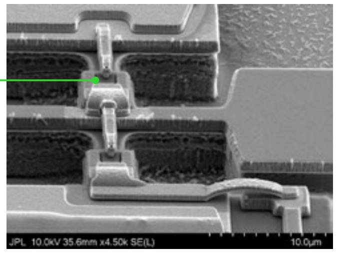
SUCH GREAT HEIGHTS



2 THz mixer



T-shaped Schottky diode



2 THz subharmonic mixer device fabricated at MDL

A state-of-the-art 2 THz limb scanning receiver will analyze the winds in Earth's thermosphere in three dimensions

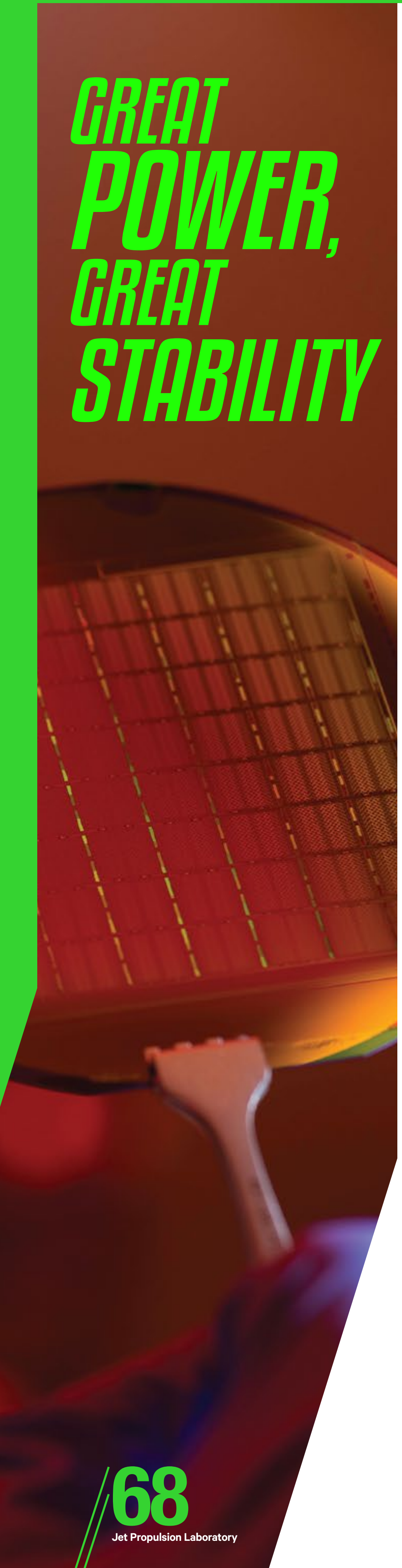
Understanding how the atmosphere behaves is crucial to understanding how Earth's climate is changing. The current understanding of the mechanisms underlying the composition, dynamics, and temperature variability of the upper atmosphere, as well as the role of dynamics of neutral atoms on ionospheric variability, depend on global measurements of lower thermospheric neutral winds, temperature, and density from a low-Earth orbit platform. Unfortunately, no reliable satellite remote sensing technique can currently provide neutral wind measurements in the critical 100-200 km altitude region with complete local time coverage and the desired spatial resolution, precision, and accuracy even though its measurement is important because it is the transition between atmosphere-like and space-like environments.

THE RECEIVER WILL FILL A KEY GAP IN DATA FROM 100-200 KM ABOVE THE EARTH'S SURFACE

Recently, MDL scientists have taken advantage of MDL's microfabrication capabilities to demonstrate the first ever room-temperature, all-solid-state heterodyne receiver capable of measuring winds in three dimensions with m/s accuracy, derived from ultra-high-spectral-resolution observations of the atomic oxygen line at 2.06 THz in Earth's thermosphere. The receiver is based on a state-of-the-art GaAs Schottky mixer at 2 THz and a state-of-the-art Schottky frequency multiplier chain at 1.0 THz, producing ~2 mW of output power. The receiver demonstrates a double-sided band (DSB) noise temperature of less than 7000 K at room temperature. The 2 THz mixer and the last-stage frequency multiplier at 1 THz were microfabricated using e-beam lithography on 4-inch GaAs wafers. In contrast, lower-frequency multipliers have been microfabricated using optical lithography with an i-line stepper on the same wafer size.

This breakthrough accomplishment will enable JPL to propose an instrument for NASA's Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC) call. The DYNAMIC mission, part of the Solar Terrestrial Probes (STP) program, was recommended as a top priority in the 2013 Solar and Space Physics Decadal Survey and is baselined to be a two-satellite mission to delineate the dynamic behavior and structure of the ionosphere, thermosphere and mesosphere system. If funded, the class-D mission, led by the Applied Physics Lab (APL) at Johns Hopkins University, will help answer two important scientific questions.

The first is **"How is our planetary environment changing, and what are the underlying causes?"** The second question is more specific: **"How do neutrals and charged particles interact to create multi-scale structures in the upper atmosphere?"**

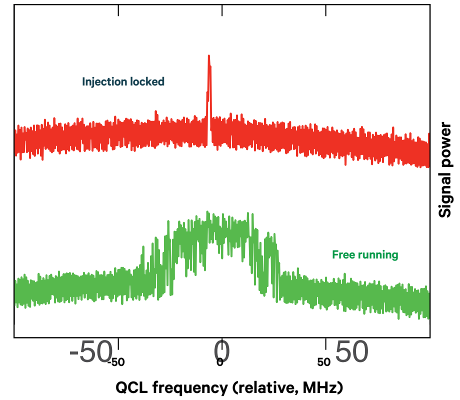


GREAT POWER, GREAT STABILITY

Combining technologies fills the THz gap

The THz frequency range is rich in molecular and atomic signatures that can be useful for studying various aspects of space science, from mapping massive interstellar gas clouds where young stars are being born to studying the chemistry of planetary atmospheres and measuring water on the Moon and comets. However, the THz range remains a significant technology gap in NASA's capabilities due to various engineering challenges in developing sources, detectors, and other components. Two promising sources of THz radiation are Schottky diode frequency multiplier chains (FMCs, with an electronic source) and quantum-cascade lasers (QCLs, with an optical source). FMCs have extremely narrow linewidths (Hz scale) and precise frequency control, which are essential performance metrics for high-resolution spectroscopy, but they offer relatively low power levels (microwatts). QCLs can provide much higher power levels (milliwatts), but their exact output frequency is not easily controlled and is much less stable (MHz scale). JPL's Submillimeter Wave group is a world leader in developing state-of-the-art THz FMCs, and more recently, they have begun developing THz QCL capabilities.

COUPLING FMCs AND QCLs MAXIMIZES FREQUENCY CONTROL AND POWER



Comparison between free-running and injection-locked QCL outputs

Both of these technologies depend on MDL's facilities. In 2022, the Submillimeter Wave group demonstrated the injection locking of a THz QCL using an FMC source — by coupling mere nanowatts of power from an FMC source into a QCL laser cavity, the QCL output locked to the injected FMC signal, transferring absolute frequency control and stability to the QCL; this demonstration is the subject of a forthcoming publication (see graph above).

This innovation brings out the best of both worlds, with high power from the QCL and excellent frequency control from the FMC. In a sense, the QCL is acting as an amplifier for the FMC, with several orders of magnitude of gain. With large fractional frequency tuning (<10%) available from both the QCLs and FMCs, the technologies can be combined to make compact, high-power, high-resolution, broadband tunable THz sources, which are currently almost nonexistent. Such sources can pave the way for powerful remote and in situ spectroscopy instruments for exploring the ever-elusive THz universe.

Building a bridge between RF and optical technologies

Peer-Reviewed Journal Publications

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2. Cieslarova, Z. et al. From Microorganisms to Biosignatures: Subcritical Water Extraction as a Sample Preparation Technique for Future Life Detection Missions. Geophysical Research Letters, vol. 49. https://doi.org/10.1029/2022GL098082
3. Chen, X. et al. Mid-and long-wave infrared point spectrometer (MLPS): a miniature space-borne science instrument. Optics Express, vol. 30, pp. 17476-17489. https://doi.org/10.1364/OE.456057
4. Cultrera, L. et al. Photoemission characterization of N-polar III-Nitride photocathodes as candidate bright electron beam sources for accelerator applications. J. Appl. Phys., vol. 131, 124902. https://doi.org/10.1063/5.0076488
5. Ferreira Santos, M.S. et al. Radiation-Tolerant Contactless Conductivity Detector for Spaceflight Applications., Acta Astronautica, vol. 190 pp. 299-307. https://doi.org/10.1016/j.actaastro.2021.10.023.
6. Guzman, P. et al. Thermal-piezoresistive pumping on double SiC layer resonator for effective quality factor tuning. Sensors and Actuators A: Physical, vol 343. https://doi.org/10.1016/j.sna.2022.113678
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8. Hoehler, T. et al. Leveraging Earth Hydrosphere Science in the Search for Life on Ocean Worlds. Oceanography, vol. 35, pp. 23-29. https://doi.org/10.5670/oceanog.2021.412
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10. Kehl, F. et al. Providing Enhanced Migration Time Reproducibility with a High-Voltage-Compatible Flow Sensor for Capillary Electrophoresis. Analytical Chemistry, vol. 94, pp. 5734-5740. https://doi.org/10.1021/acs.analchem.2c00038
11. Kim, B. et al. Systematic modeling of electrostatic radiation shields for deep space flight. Radiation Physics and Chemistry, vol. 193, 110007. https://doi.org/10.1016/j.radphyschem.2022.110007
12. Kim T. et al. A multi-modal volumetric microscope with automated sample handling for surveying microbial life in liquid samples. Front. Astron. Space Sci., vol. 9, 763329. https://doi.org/10.3389/fspas.2022.763329
13. Kok, M.G.M. et al. A Novel and Sensitive Method for the Analysis of Fatty Acid Biosignatures by Capillary Electrophoresis-Mass Spectrometry. Analytical Chemistry, vol. 94, pp. 12807–12814. https://doi.org/10.1021/acs.analchem.2c02716. Article chosen for ACS Editor's Choice Award 2022
14. MacKenzie, S. et al. Science Objectives for Flagship-Class Mission Concepts for the Search for Evidence of Life at Enceladus. Astrobiology, vol. 22, pp. 685-712. https://doi.org/10.1089/ast.2020.2425
15. Madzunkov, S.M. et al. Data analysis and isotopic ratios measured onboard the Spacecraft Atmosphere Monitor. International Journal of Mass Spectrometry, vol. 477, 116847. https://10.1016/j.ijms.2022.116847
16. Madzunkova, S. and Nikolić D., Method for accurate detection of amino acids and mycotoxins in planetary atmospheres. Life, vol. 2, 2122 ; https://10.3390/life12122122
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2. Ballew, C. et al. Volumetric Metaoptics for Compact and Low-Power Spectroscopy, 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), Delft, Netherlands, 2022, pp. 1-2, https://doi.org/10.1109/IRMMW-THz50927.2022.9895578.
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4. Bidney, G.W. et al. Fabrication of 3-D light concentrating microphotonic structures by anisotropic wet etching of silicon, Proc. SPIE 12012, Advanced Fabrication Technologies for Micro/Nano Optics and Photonics XV, 120120B (5 March 2022); https://doi.org/10.1117/12.2610426
5. Coskun, M.B. et al. A MEMS Microvalve Array For Gas Flow Control, 2022 IEEE 35th International Conference on Micro Electro Mechanical Systems Conference (MEMS), Tokyo, Japan, 2022, pp. 466-469, https://doi.org/10.1109/MEMS51670.2022.9699667
6. Gunapala, S. et al. Compact fire infrared radiance spectral tracker (c-FIRST), Proc. SPIE 12264, Sensors, Systems, and Next-Generation Satellites XXVI, 122640E (28 October 2022); https://doi.org/10.1117/12.2631509
7. Gunapala, S. et al. Mid-wavelength and long-wavelength infrared focal planes for smallsat applications, Proc. SPIE 12091, Image Sensing Technologies: Materials, Devices, Systems, and Applications IX, 1209102 (30 May 2022); https://doi.org/10.1117/12.2619573 (Invited Talk)
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25. Ting, D.Z. et al. InAs/InAsSb Type-II Strained Layer Superlattice Barrier Infrared Detectors, 2019 IEEE Photonics Conference (IPC), San Antonio, TX, USA, 2019, pp. 1- https://doi.org/10.1109/IPCon.2019.8908487

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27. Yousuf, S.M.E.H. et al. Retaining High Q Factors in Electrode-Less Aln-On-Si Bulk Mode Resonators with Non-Contact Electrical Drive, 2022 IEEE 35th International Conference on Micro Electro Mechanical Systems Conference (MEMS), Tokyo, Japan, 2022, pp. 979-982, https://doi.org/10.1109/MEMS51670.2022.9699607

Book Contributions

1. Otterstrom, N.T., Kittlaus, E.A., Sohn, D.B., & Bahl, G., Nonreciprocity in Brillouin scattering. In Semiconductors and Semimetals: Brillouin Scattering Part 2. Academic Press, Inc. (2022). https://doi.org/10.1016/bs.semsem.2022.05.006

2. Thompson, L.F., Gluyas, J.G., Klinger, J., Kudryavtsev, V.A., Lincoln, D.L., Woodward, D. & Coleman, M. (2022) Muography, a Key Technology for Monitoring Carbon Geostorage. In Muography: Exploring Earth's Subsurface with Elementary Particles, pp. 185-197, American Geophysical Union, John Wiley & Sons Inc. (2022). https://doi.org/10.1002/9781119722748.ch14

New Technology Reports

1. Hoenk, M.E. & Jewell, A.D. Ultra-Low Temperature Silicon Molecular Beam Epitaxy using Dopant-induced Catalysis of Hydrogen-terminated Silicon, NTR 52493.
2. Hoenk, M.E. et al. Enhanced 2D-doping surface passivation structure and process. NTR 52419.
3. Hoenk, M.E. et al. Design Concept for an EUV Imager at GEO. NTR 52270.
4. Jewell, A.D. et al. Process for area-selective atomic layer deposition of antireflection coatings and filters. NTR 52422.
5. White, V. & Yee, K. Improved black silicon slits. NTR 52556.

Awards and Recognition by External Organizations

1. David Ting was awarded the NASA Exceptional Public Achievement Medal for his invention of the the type-II superlattice (T2SL) barrier infrared detector (BIRD).
2. Maria F. Mora was awarded the NASA Early Career Achievement Medal for significant early career achievement in the development of chemical analyses for ultrasensitive life detection measurements on future spaceflight missions.
3. Sarath D. Gunapala received the Quantum Devices Award from the International Symposium on Compound Semiconductors Conference for his contributions to the III-V quantum structure infrared detectors and focal plane arrays.
4. Andrew Beyer, Bruce Bumble, Daniel Cunnane, Peter Day, Pierre Echternach, Byeong Ho Eom, Changsub Kim, Henry Leduc, Roger O'Brient, Tobias Wenger received the NASA Group Achievement Award for the development of innovative inductance detectors and traveling-wave parametric amplifiers.
5. April Jewell was nominated and confirmed as Chair-Elect of the American Vacuum Society's Thin Film Division, taking on the role of Division Program Chair for the Society's 2023 Symposium. She will assume the role of Division Chair in 2024.

MDL Equipment Complement

Material Deposition

- Electron-Beam Evaporators (8)
  - 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 IR detector Evaporator
- Thermal Evaporators (4)
  - KJL Indium Evaporator
  - Denton Indium Evaporator
  - SIO Evaporator
  - 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.
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Beneq TFS-200 Atomic Layer Deposition (ALD) System
- 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 System for Dielectrics and Metals (SIS)
- Lesker #2 Ultra-High-Vacuum (UHV) Sputtering System for Superconducting Materials (SIS)
- Lesker Silicon Dioxide Sputter (Low Loss Dielectric) UHV Sputtering system (SIS)

Lithographic Patterning

- 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 (0.15-µm res.)
- Karl Suss MJB3 with backside IR Contact Aligners:
- Suss MA-6 (UV300) with MO Exposure Optics upgrade
- Suss BA-6 (UV400) with jigging supporting Suss bonder

Resist Processing Equipment

- Site Services Tractix Wafer Coater/Developer Dispense System
- 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
- Yield Engineering System (YES) Reversal Oven
- Thermal Bake Vacuum ovens, Hotplates, Convection Ovens (16)

Dry Etching/Ashing

- Commonwealth IBE-80 Ion Mill
- YES Eco-Clean Downstream Plasma Asher
- Branson Plasma Asher
- Tepla PP300SA Microwave Plasma Asher
- 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 and 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 ICP/ALE Etcher System

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 System

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 Atomic 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 System
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- VEECO / WYKO NT 9300 Surface Profiler (including 50X optics)
- Zygo ZeMapper non-contact 3D Profile
- Thermo Scientific LCQ Fleet CE / MS (Capillary Electrophoresis / Mass Spectrometer) System
- Veeco FFP 100 4-Point Probe

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

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.

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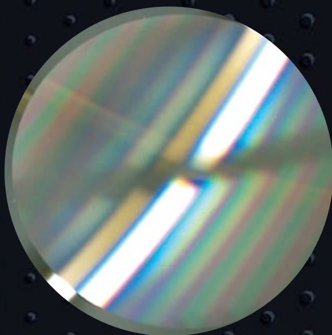

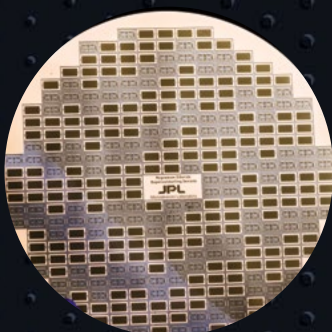

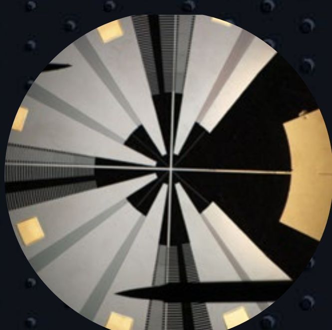

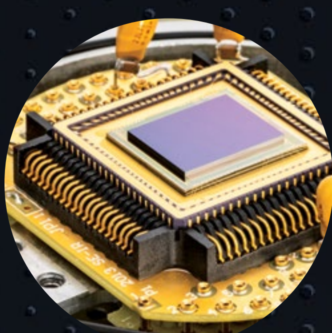

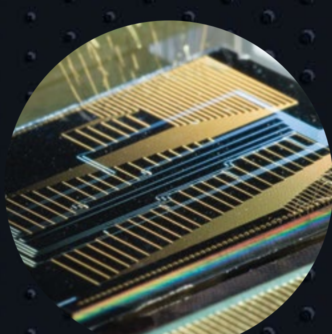

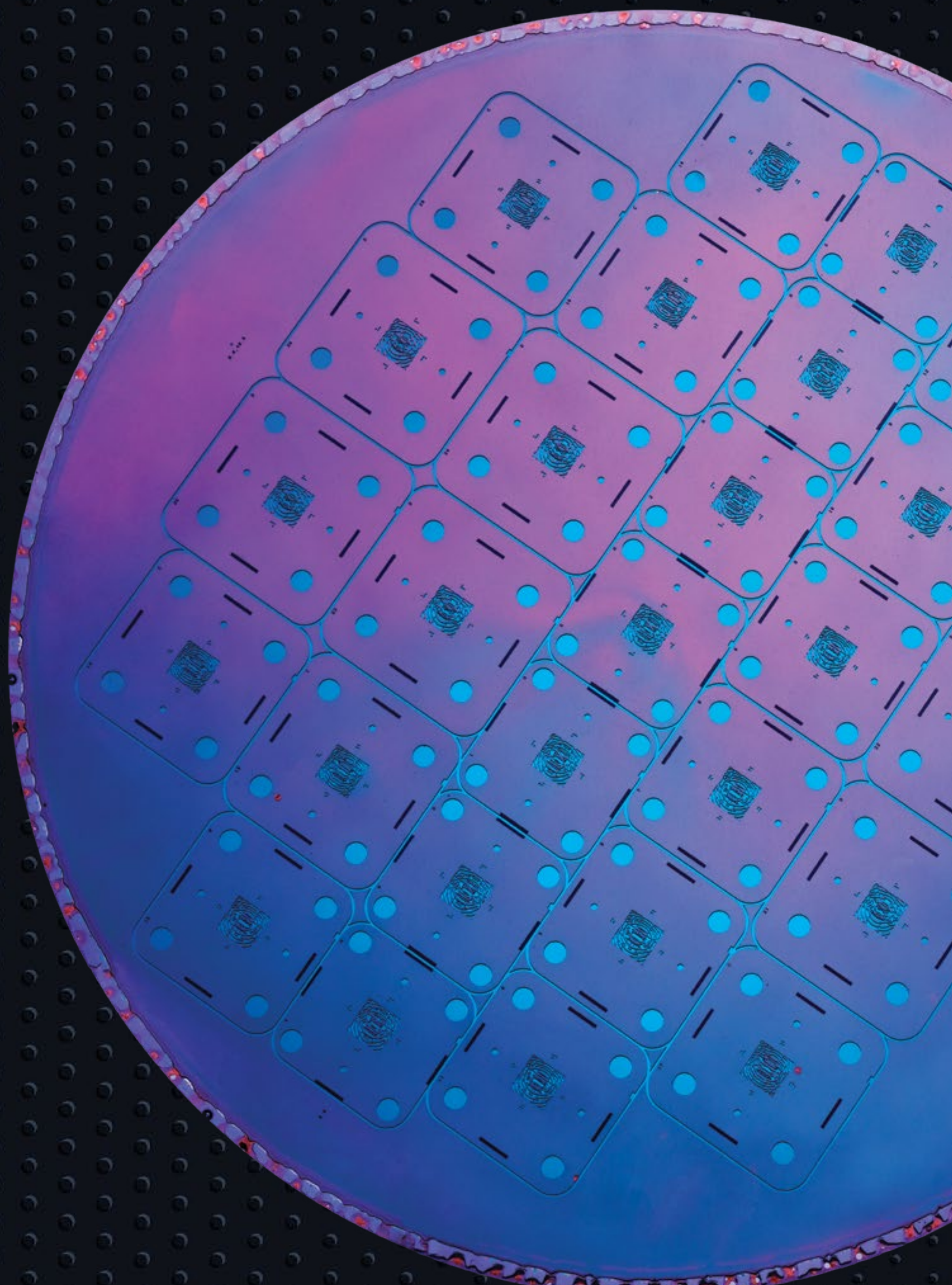

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