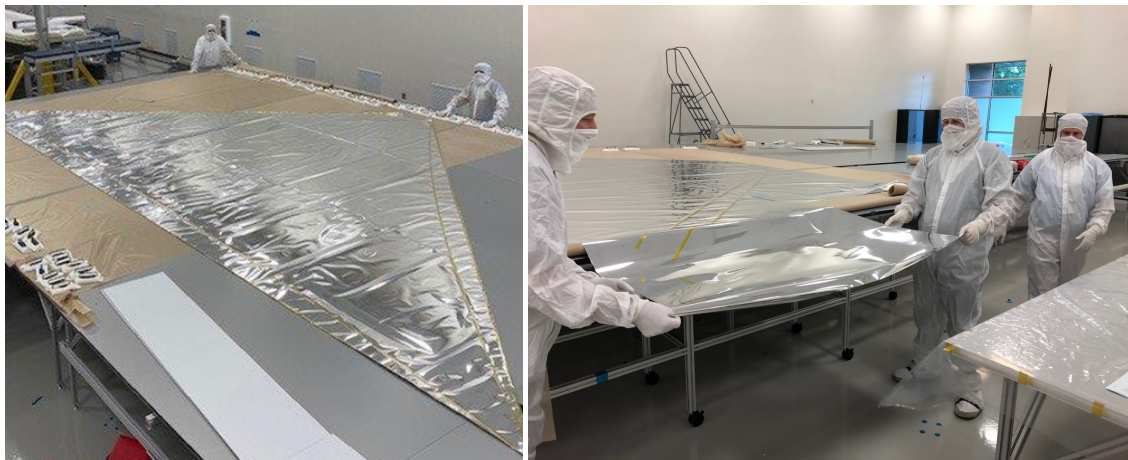


Heliophysics



Solar Cruiser engineers from NeXolve built four 1/16th scale sail quadrants within the past year for testing (left). Checking the backing on the thin film sail material (right).

Solar Sail Propulsion: Enabling New Destinations for Science Missions

Project: Solar Cruiser technology demonstration mission

Sponsoring Organization:
Heliophysics Division's Solar Terrestrial Probes Program

Project Lead: Les Johnson, NASA Marshall Space Flight Center

Snapshot: To enable missions to reach novel and otherwise difficult or impossible destinations for observing the Sun, NASA is developing the 1653 m² Solar Cruiser solar sail system for flight demonstration in 2025.

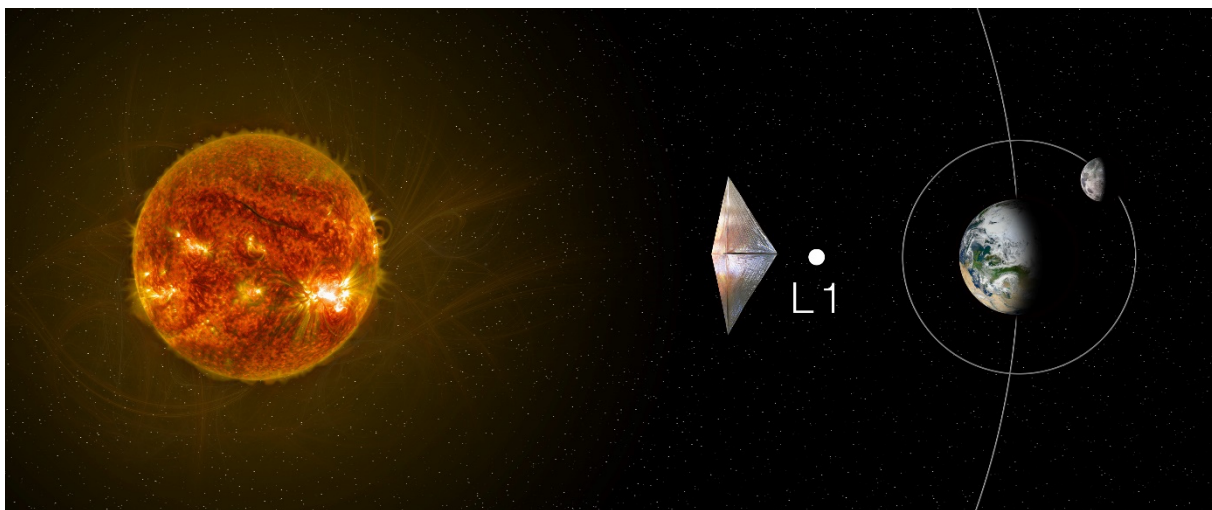
Key terms: solar sail, space weather, sunlight pressure, polyimides, composites

Leveraging technology developments to enable new and groundbreaking science is an important Science Mission Directorate goal. Solar Cruiser, a pathfinder mission sponsored by the [Heliophysics Division's Solar Terrestrial Probes Program](#), incorporates several new technologies originally developed by various organizations and integrates them to demonstrate a remarkable capability—the use of sunlight to propel a spacecraft.

The solar sail technologies demonstrated on Solar Cruiser will enable future missions to address important science questions about the Sun, its interaction with Earth, and other elements of the heliosphere. Solar Cruiser will demonstrate how solar sail propulsion can enable spacecraft to collect observations from novel vantage points that are difficult to reach and sustain. Specifically, Solar Cruiser will maintain a position sunward of Lagrange point L1—the position where Earth's and the Sun's gravity are balanced along the Sun-Earth-line. Solar Cruiser will also demonstrate technologies that will enable future missions

to improve space-weather monitoring, prediction, and science.

Solar sails use large, highly reflective, lightweight material that reflects sunlight to propel a spacecraft. The continuous photon pressure from the Sun's rays provides thrust with no need for the heavy, expendable propellants employed by conventional chemical and electric propulsion systems that limit mission lifetime and observation locations. Solar Cruiser will demonstrate the ability of solar sails to enable missions to observe the solar environment from unique vantage points of interest to heliophysics, including maintaining a satellite in a position sunward of L1. Monitoring the Sun at this orbital location is of interest not only to NASA scientists, but also to NASA's human exploration programs, which must support human spaceflight crew safety and health; the National Oceanic and Atmospheric Administration (NOAA) which is the nation's source for space weather alerts and forecasts; and the Department of Defense, which monitors space weather for interference with communications or satellites. Solar Cruiser will also demonstrate the capability to obtain sustained *in-situ* Earth magnetotail measurements and the ability to achieve and maintain a high-inclination solar orbit—a capability which future missions to image the polar regions of the Sun will require.



The Solar Cruiser will demonstrate solar sail propulsion by flying sunward of L1 and maintaining its position along the Sun-Earth-line using only reflected light for propulsion.

A team led by NASA's Marshall Space Flight Center is developing the Solar Cruiser mission to mature solar sail technology for future mission use in the 5–15-year timeframe. The Solar Cruiser team (which includes Ball Aerospace, Rocco, LLC, and subcontractor, NeXolve) is leveraging solar sail technology advancements from the last decade, including test flights of smaller sails such as those on NASA's NanoSail-D mission, led by NASA Marshall; the Japan Aerospace Exploration Agency's Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) mission; The Planetary Society's LightSail missions; as well as MSFC's planned 2021 flight of the Near-Earth Asteroid (NEA) Scout, developed by the NASA Human Exploration and Operations Mission Directorate Advanced Exploration Systems Division.

Solar Cruiser will fly a large, four-quadrant solar sail on a ten-month mission that demonstrates numerous technologies necessary to implement exciting, future missions to destinations heretofore unreachable. Solar Cruiser includes the largest sail ever flown—a 1653 m², 2.5-micron thick reflective sail that is thinner than a human hair. Solar Cruiser also includes four 29.5-m, lightweight, composite booms to deploy the sail; embedded thin film photovoltaics to demonstrate a new method of power generation; and embedded Reflective Control Devices (RCDs) that will help keep the sail stable.

The sail membrane is manufactured using a thin-film polyimide (clear polymer 1, or CP1) coated with aluminum to make it reflective. The CP-1 sail membrane was developed by NASA and licensed by NeXolve over two decades ago and was successfully flown on NanoSail-D. CP1 was chosen for Solar Cruiser because of its lengthy flight heritage, demonstrated properties that are suitable for the Solar Cruiser and future missions, and availability. It is also scalable to sails of virtually any size, from the 10 m² flown on NanoSail-D, to sails greater than 10,000 m².

On previous missions, including NanoSail-D and the LightSails, solar sails were deployed and tensioned using metallic Triangular, Rollable and Compressible (TRAC™) booms—a design originated by the U.S. Air Force and licensed by Rocco, LLC. The upcoming NEA Scout mission will also use these metallic booms. These extremely long booms have a triangular cross-section that can be forced flat, enabling them to be rolled onto a spool for stowage. Metallic TRAC™ booms, however, are not extensible to Solar Cruiser-class sails due to their mass and thermal expansion properties. Instead, Rocco, LLC developed booms made from composite materials via NASA's Small Business Innovation Research (SBIR) program.



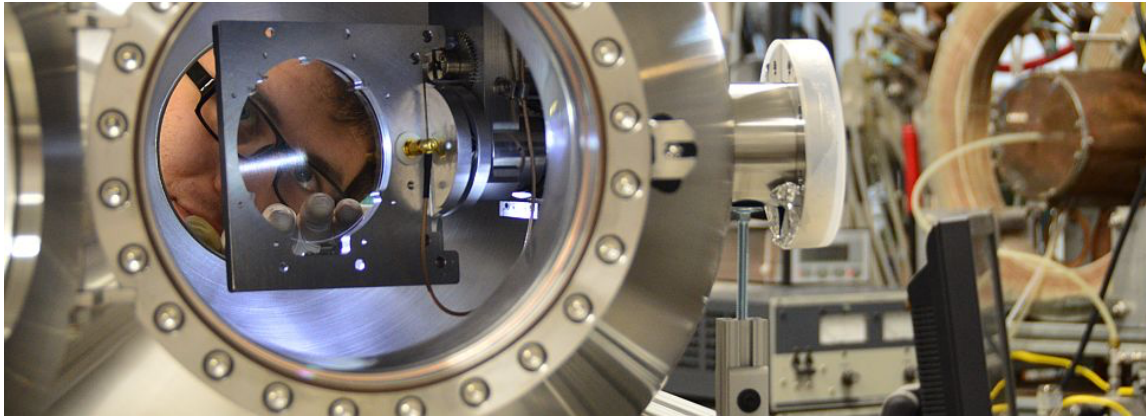
Four one-quarter scale composite booms built and deployed from a prototype sail deployer.

Solar Cruiser will use an Active Mass Translation (AMT) device originally developed by NASA Marshall for the NEA Scout mission to actively adjust the spacecraft center of (light) pressure relative to its center of mass to keep the sail stable and to support steering and navigation. In addition, RCDs, composed of a thin film that can be switched from reflective to transmissive with an applied voltage, will contribute to maintaining the sail's stability during flight. The concept for these RCDs was originally developed via a Space Technology Mission Directorate (STMD) Early Career Faculty grant; STMD subsequently sponsored NeXolve to advance the technology for use on Solar Cruiser.

Solar Cruiser will also demonstrate the use of thin-film photovoltaic cells embedded in the sail to generate electrical power. First developed at NASA Marshall by STMD, this technology was further refined via an STMD Early Career Initiative as part of the Lightweight Integrated Solar Array and anTenna (LISA-T) project and will be demonstrated on Solar Cruiser to provide power for future missions.

Solar Cruiser is scheduled for launch in 2025. Once it successfully demonstrates these technologies, solar sail propulsion using large, high-performance sails will be available for future science missions, providing a new capability for NASA and the nation.

Astrophysics



MIT postdoc Brandon Chalifoux mounting a test mirror for stress figure correction using ion implantation. (Credit: Ralf Heilmann)

Nanofabricated Mirrors and Gratings Will Enable More Powerful Space Telescopes

Project: Sub-arcsecond X-ray telescope optics and high-resolution, high-efficiency X-ray transmission grating spectrometers

Sponsoring Organization:

Astrophysics Division's APRA and SAT Programs

Project Leads: Dr. Mark Schattenburg and Dr. Ralf Heilmann, Massachusetts Institute of Technology

Snapshot: A NASA-sponsored team at the MIT Space Nanotechnology Lab is developing high-performance space instrumentation for more powerful future X-ray telescopes that will study the dynamics of the high-energy universe.

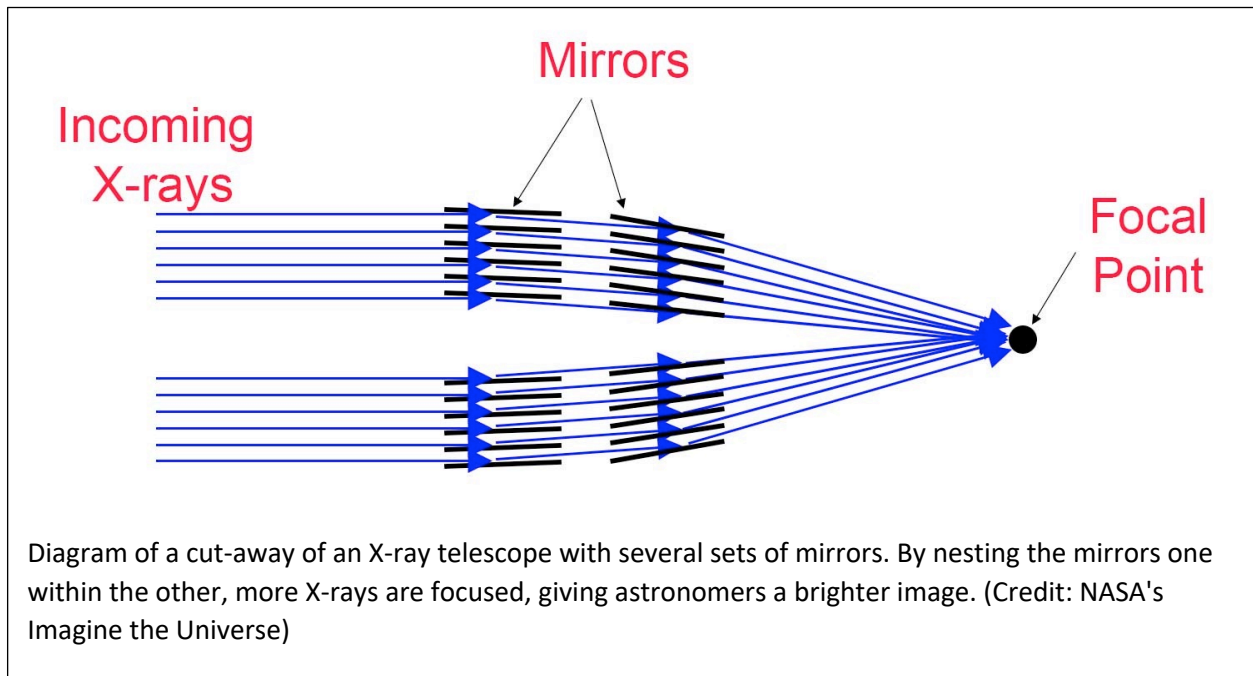
Key terms: X-ray astronomy, X-ray mirror, X-ray diffraction grating, critical-angle transmission grating, stress-based figure correction, thin-film stress, thermal oxide, Chandra, Lynx, Arcus

In the 50 years since the launch of [*Uhuru*](#), the first X-ray astronomy satellite, our knowledge about the high-energy universe has exploded. Measurements of celestial X-ray emission and absorption have taught us about supermassive black holes, neutron stars, accretion disks, and many more phenomena in the high-temperature universe. Naturally, many new questions have arisen that cannot be answered with old technology. Today, NASA's great X-ray observatory [*Chandra*](#) has lasted over two decades in space, and the Agency is considering potential future strategic mission concepts with vastly improved performance such as [*Lynx*](#). This improved performance relies on cutting-edge technology, such as ultra-precise X-ray mirrors and high-performance X-ray diffraction gratings. These mirrors and gratings are tens to hundreds of millimeters in size and sub-millimeter thin, but must be fabricated, shaped, and assembled with nanometer precision.

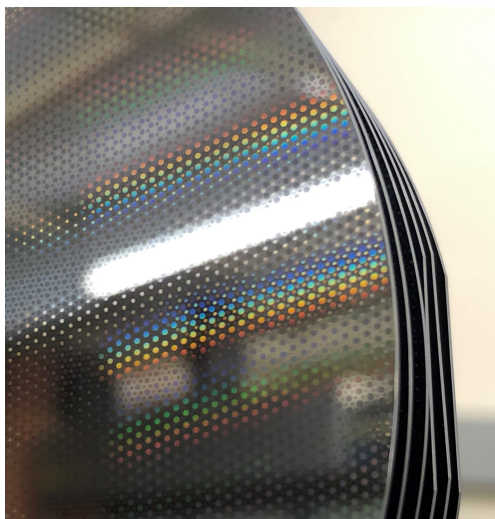
X-rays are highly energetic electromagnetic radiation, mostly known for their ability to penetrate soft organic tissue for the imaging of bones or teeth. In our universe, X-rays are generated by highly energetic processes, usually associated with temperatures in the range of millions to tens of millions of degrees. Examples of X-ray-generating environments include the coronas of stars, accretion disks in binary systems, and active galactic nuclei. In addition, gases and plasmas between these sources and Earth can absorb some of these X-rays, so X-ray observations also teach us about the dynamic interstellar and intergalactic material. Astronomers need to image X-ray sources with high angular resolution and break down the X-ray light into its finest spectral components to understand the conditions and abundance of elements at the source and the processes that generate the X-rays. A NASA-sponsored team at the Kavli Institute's Space Nanotechnology Lab (SNL) at the Massachusetts Institute of Technology (MIT) is working to develop advanced mirrors and gratings that will enable future X-ray telescopes.

More Precise Mirrors

Building an X-ray telescope is challenging, mostly due to the way X-rays interact with matter. In astronomy most of the X-rays of interest are less energetic ("softer") than medical X-rays and are more easily absorbed by matter. In addition, the index of refraction for X-rays is very close to one for most materials, which means that lenses can barely bend X-rays. Both of these reasons make it impractical to build traditional telescope lenses for imaging or prisms for spectral analysis of celestial X-ray sources. Instead, in a method akin to skipping rocks on a pond, scientists use mirrors to reflect the X-rays at very shallow angles (below the so-called critical angle) toward a focal point (see figure below). It can take hundreds of nested shells of mirrors to densely fill the aperture of a large telescope. The mirrors must be as thin as possible to avoid wasting the precious collecting area and to keep mass low. Each mirror must have a precisely bent shape and must be precisely aligned with respect to all the other mirrors. For a future mission concept such as Lynx, the requirement for the telescope angular resolution is half an arcsecond. For best reflectivity the mirrors must be coated with very thin, nanometer-thick films, typically made of metals. However, metal films are inherently stressed and can deform the thin mirrors by several micrometers, which is beyond acceptable tolerances. In addition, the amount and distribution of stress in the film is often difficult to predict or control.



A team at the Kavli Institute's SNL has explored ways to correct for mirror bending from coating stress by imparting a counter-balanced stress on the mirrors' back side in three different ways: ion implantation, lithographic patterning of thermal oxide, and laser micromachining. Each method calls for measuring the mirror shape before and after coating and calculating the coating's stress distribution from the measured deformation. Then a correction stress map is calculated for the mirror's back side that would bend the mirror back into its original shape. Next a 2D correction or "dose" map is generated that will lead to the desired correction stress distribution, and the correction is applied to the mirror's back side using one of the three methods, as discussed below.

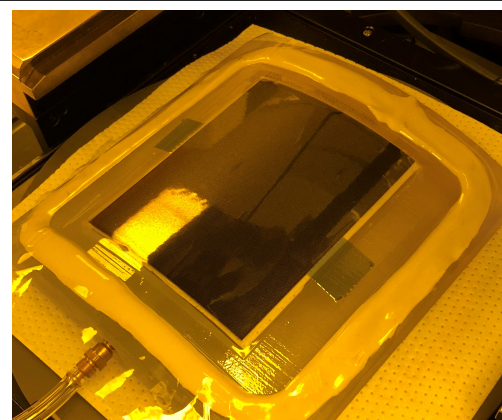


Silicon wafers with stress correction patterns etched into a thermal oxide layer. (Credit: Youwei Yao)

The ion implantation method shoots high-energy ions into the mirror's back side, creating a stressed layer a few micrometers below the surface that bends the mirror back into shape. The thermal oxide patterning method first grows a thermal oxide film – which has a very well-defined stress exceeding the metal film stress – on the back of a silicon mirror, bending the mirror in the opposite direction. Then a specially designed 2D honeycomb pattern with varying wall thicknesses is etched into the thermal oxide, removing just enough stressed material to compensate for the metal film stress. The laser micromachining method also uses an overcompensating thermal oxide film on the back of the mirror, but with this method the excess oxide is removed in a designed pattern by femtosecond laser pulses (lasers whose pulses are less than a trillionth of a second long).

A key problem common

to all three approaches is the accurate measurement of the shape of the mirrors: they are so thin that they sag under their own weight, and the forces required to hold them in place can easily deform them by many times the nano-scale tolerances. The near-cylindrical shape of the mirrors provides additional measurement and processing challenges. So far, the thermal oxide patterning method has shown the most success, demonstrating shape improvement of Lynx-prototype, iridium-coated, silicon mirrors fabricated by a team at Goddard Space Flight Center (GSFC) by a factor of five, and reducing the effect of film stress to the level of about 0.5 arc-second slope error (root-mean-squared).



Cylindrical silicon X-ray mirror in the curved-mirror exposure tool for lithographic patterning of the stressed thermal oxide layer. (Credit: Youwei Yao)

The team continues to improve these methods and extend them to correct arbitrary deformations.

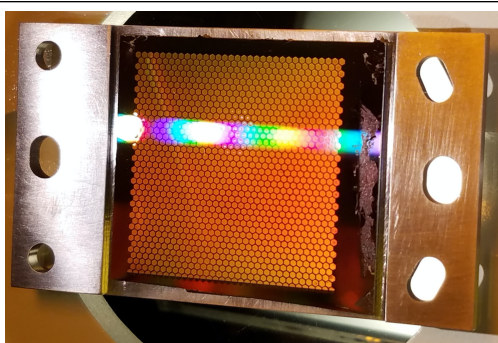
High-performance Gratings

Mirrors cannot separate X-rays according to their energy or wavelength. For the softest X-rays of astrophysical interest, separation is best accomplished using a diffraction grating spectrometer, which splits the X-rays into different diffraction orders, separated by angle according to their wavelengths, such that they can be detected by a CCD camera. The MIT team has recently developed a novel X-ray transmission grating that provides orders-of-magnitude performance improvement over Chandra-era instrumentation. The transmission geometry has relaxed alignment tolerances and needs only very thin, low-mass gratings. Absorption is minimized by allowing the X-rays to transmit through the empty space between the freestanding grating bars. And similar to the X-ray mirrors described above, the grating

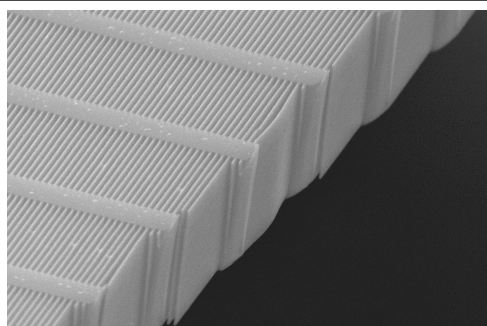
bars are inclined at a small angle such that the X-rays efficiently glance off the grating bars and disperse into diffraction orders at larger angles than conventional transmission gratings, leading to better spectral resolution. More energetic (“harder”) X-rays undergo very little diffraction or absorption as they move through the grating on their way to the telescope imaging focus, where an X-ray microcalorimeter can perform imaging spectroscopy with high energy resolution.

For this design to work well the grating bars have to be tall and very thin. The grating pitch was chosen to be 200 nanometers, resulting in 4-6 micrometer tall and 40-60 nanometer-wide grating bars with ultra-high aspect ratios of over 100. The roughness of the sidewalls must be less than a few nanometers and the average pitch has to be constant to better than 20 picometers over tens of thousands of grating bars. This so-called critical-angle transmission (CAT) grating is in essence a super-precise array of thousands of nanomirrors.

CAT gratings are fabricated from silicon-on-insulator (SOI) wafers, comprised of a thin, 4-6 micrometer silicon layer on a 0.5 mm-thick silicon wafer, separated by a



Picture of a > 900 mm² CAT grating, mounted to a metal holder. The “rainbow” pattern is due to diffraction of visible light from the cross supports. The 1 mm-pitch honeycomb pattern is etched out of the 0.5 mm-thick silicon wafer and provides strength to large gratings. (Credit: Ralf Heilmann)

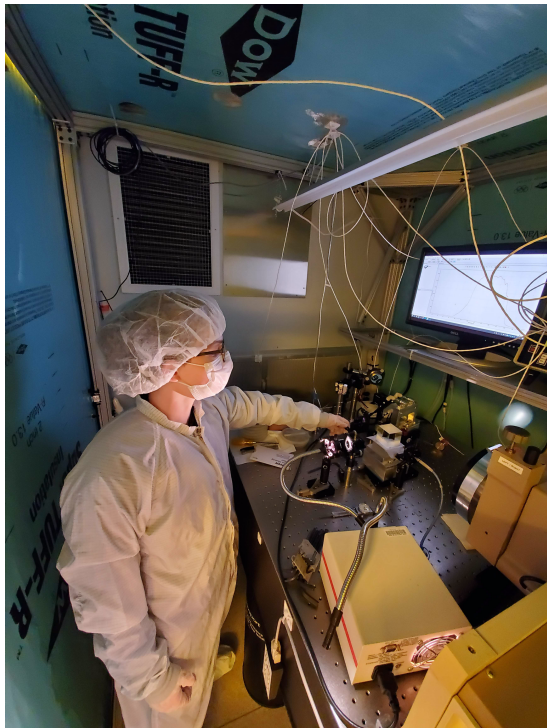


Scanning electron micrograph of a cleaved CAT grating, showing hundreds of 200 nm-period grating bars and the orthogonal, 5 micrometer-period cross supports. X rays enter from the top, diffract through the gaps between grating bars, and exit out the bottom. (Credit: Alexander Brucoleri)

thin layer of buried silicon

oxide. The first prototype gratings were fabricated using a potassium hydroxide (KOH) etching process that produced smooth grating walls, but also resulted in trapezoidal cross-supports that blocked many of the incoming X-rays. To solve this problem the team switched to a high-aspect-ratio etching process using a deep reactive-ion etch (DRIE) technique developed by a NASA-sponsored team at the University of Michigan, followed by a brief KOH etch that “polishes” the grating sidewalls that are left rough from DRIE.

The team has produced CAT gratings larger than 30 x 30 mm² that have shown absolute diffraction efficiency (i.e., the percentage of X-rays that are diffracted and not lost, and can be used for spectroscopy) over 30% in the soft X-



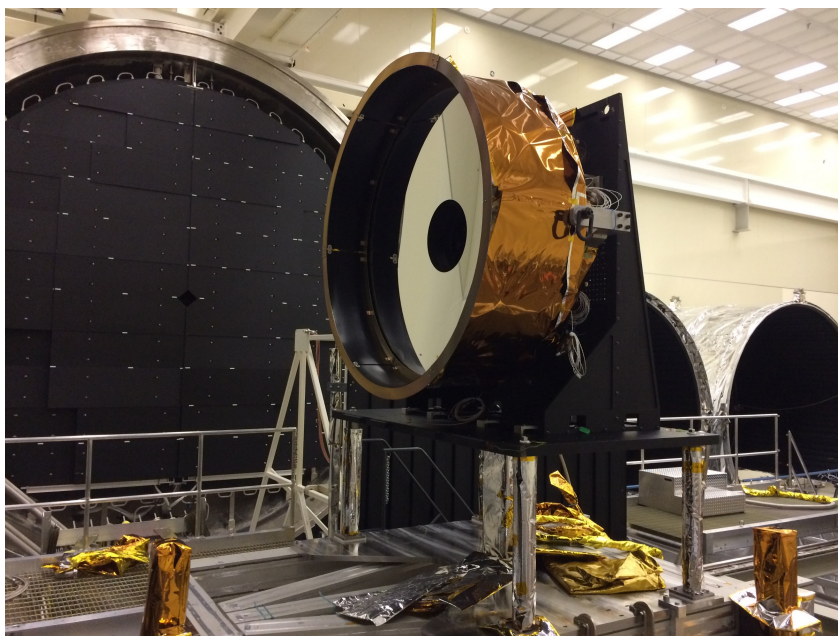
MIT graduate student Mallory Whalen measuring the optical properties of a CAT grating inside a temperature-controlled cleanroom enclosure. (Credit: Mallory Whalen)

ray band (Chandra grating efficiency is in the range of 1-10%). The team has built small arrays of aligned CAT gratings and a prototype CAT grating spectrograph using NASA GSFC X-ray-focusing mirrors that has demonstrated spectral resolving power (the ability to distinguish between similar wavelengths) greater than 10,000—which is over ten times better than that of Chandra.

So far, all of these CAT gratings have been made with a painstaking and highly manual “beaker and tweezer” approach in MIT student clean rooms—an effort that typically renders one grating from a 100 mm SOI wafer. However, a flight X-ray grating spectrograph needs thousands of square centimeters of grating area, which means hundreds of gratings. The MIT researchers, in collaboration with the *Arcus* Grating Explorer team (PI Randall Smith, Smithsonian Astrophysical Observatory) and MIT Lincoln Labs, are currently developing manufacturing methods that would allow high-volume production using 200 mm SOI wafers and commercial optical projection lithography stepper/scanner tools. The successful high-volume fabrication of CAT gratings could provide this enabling technology at affordable cost and short schedule for potential pathbreaking high-

resolution X-ray spectroscopy missions such as *Arcus*, soft X-ray spectro-polarimetry missions such as *REDSoX*, and for a next-generation grating instrument on a future mission concept such as *Lynx*.

The team continues to advance CAT grating spectrometer Technology Readiness Levels (TRLs) and improve the performance of fabricated gratings, in particular by making deeper grating bars and optimizing the strength and transmission of the support mesh. Team members are also developing improved metrology, alignment, and assembly tools that will be critical in a flight program.



1.5-meter ULE® mirror in 25-zone thermal assembly ready for environmental testing at MSFC's X-Ray and Cryogenic Facility (Image credit: NASA MSFC)

Controlling the Temperature of Telescope Mirrors to Search for Earth-like Planets

Project: Predictive Thermal Control (PTC) project

Sponsoring Organization:

Astrophysics Division Strategic Astrophysics Technology (SAT) Program

Project Leads: Dr. H. Philip Stahl and Thomas Brooks, NASA Marshall Space Flight Center (MSFC)

Snapshot: Active thermal control technology helps enable large ultra-stable telescopes needed to detect and characterize Earth-like planets around other stars.

Key terms: thermal control, space telescopes, exoplanet science

“Are we alone in the universe?” may be one of the most compelling questions of our generation. Direct imaging of planetary systems around other stars to detect and characterize Earth-like planets that could sustain life requires telescopes that are larger and more stable than any previous telescope. To respond to this challenge, NASA has been developing technologies to achieve ultra-stable telescopes since 2011.

Because an Earth-like planet is 10 billion times fainter than its star, it is necessary to block nearly all of the star’s light before we can see the planet. One way to block this light is with a coronagraph. But, any

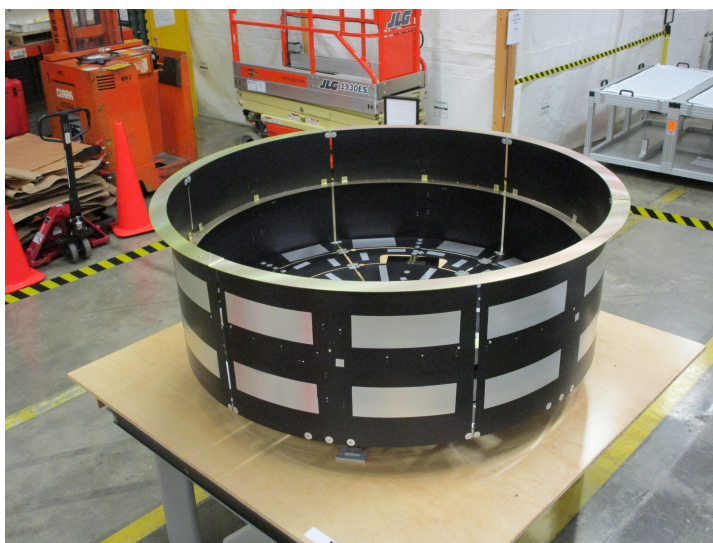
instability in the telescope – such as misalignment between the mirrors or a change in the mirror’s shape – will allow the starlight to “leak” through the coronagraph. The resulting glare will “hide” the

planet. To detect an Earth-like planet with a coronagraph requires a telescope whose optical quality is stable to better than 10 picometers per 10 minutes – which is about 1 million times smaller than the width of a human hair.

According to NASA Predictive Thermal Control (PTC) project lead, Dr. Stahl, “Picometers are very small, and measuring telescope stability to picometer levels is virtually impossible. Therefore, to predict on-orbit performance we perform STOP analysis – we model a telescope’s Structural Thermal Optical Performance based on its measurable physical properties.”

For example, the stability of a telescope depends on the material properties of its mirrors and structure and the thermal changes it experiences. An object’s coefficient of thermal expansion (CTE) describes how its dimensions change as the temperature changes. The lower the CTE, the smaller the change. The mirrors in optical wavelength space telescopes such as the Hubble Space Telescope, the Kepler Mission, and the upcoming Roman Space Telescope are made from materials with ultra-low CTE. These materials have CTEs that vary by less than 5 parts-per-billion per degree Kelvin (5 ppb/K). Thus, to achieve the 10 picometer stability required to enable detection of Earth-like planets, a telescope’s mirrors must have a temperature stability of less than 2 milli-K (mK).

The PTC project team at NASA’s Marshall Space Flight Center (MSFC) has demonstrated technology to enable ultra-stable thermal control in large space telescopes. MSFC and its industrial partner L3Harris of Rochester, NY designed, built, and integrated a 25-zone active thermal control system with a 1.5-meter Ultra-Low Expansion (ULE®) glass mirror.



The thermal assembly has 25 independent zones distributed around the perimeter (12 zones) and radially on the back plate (13 zones) to heat the mirror to its desired operating temperature. The zones enable the assembly to actively correct or compensate for thermal gradients introduced into the mirror as the telescope slews in space relative to the Sun – keeping the mirror’s temperature stable to better than 2-mK. (Image credit: L3-Harris Corp.)

When tested in a space like thermal-vacuum environment at the MSFC X-Ray and Cryogenic Facility (XRCF), the system was able to correct thermal gradients in the mirror with an accuracy of 2K and maintain that correction with a stability of 2mK. In addition to correcting for thermal gradients, it was possible to use the zonal-thermal system to correct small mirror surface errors with a correctability of 1 nm/K peak-to-valley.



Team members in the MSFC X-Ray and Cryogenic Facility (XRCF). Pictured left to right: Ron Eng, Tomasz Lis (reflected in the mirror's surface), and Ernest Wright. The XRCF is capable of characterizing the cryogenic performance of large mirrors to temperatures as low 30K. (Image Credit: Mark T. Stahl, NASA MSFC)

According to Dr. Stahl, "The purpose of technology development is to anticipate and solve problems to enable missions before a mission knows that it has a need. And, it is satisfying when a developed technology enables or enhances a mission."

Since 2011, NASA's Astrophysics Division has invested in mechanical and thermal technology to design, build and control ultra-stable telescopes. Technologies developed by PTC and its precursor study – Advanced Mirror Technology Development (AMTD) – are under consideration for the Roman Space Telescope as well as several potential future missions.

Earth Science



Two images of the NASA Jet Propulsion Laboratory, California Institute of Technology HOT BIRD Team: a photo from a visible light camera (top) and an infrared image taken with a HOT BIRD camera (bottom).

The 'Bird' with an Eagle Eye...for Infrared

Project: Mid-Wavelength and Long-Wavelength Infrared Focal Plane Arrays for Earth Science Applications

Sponsoring Organization: Earth Science Division's Advanced Component Technology (ACT) Program

Project Lead: Dr. Sarath Gunapala, NASA Jet Propulsion Laboratory, California Institute of Technology

Snapshot: NASA is sponsoring development of high-performance infrared sensors with reduced requirements for cooling onboard satellites; these new sensors could potentially be flown on small satellite platforms like CubeSats.

Key terms: infrared radiation, focal plane array, barrier infrared detectors, high operating temperature, metasurface, flat lens, digital focal planes

HOT BIRD isn't hot or a bird. It's the world-class infrared detector that could revolutionize the way we see our planet from space. A NASA-sponsored team at the Jet Propulsion Laboratory is developing highly sensitive infrared (IR) detectors that could operate onboard satellites without the usual ultra-low cooling equipment typically required. These High Operating Temperature (HOT) Barrier Infrared Detectors (BIRDs) are cheaper to manufacture and easier to accommodate onboard satellites than the IR detectors presently used in space.

Many satellites employ infrared-sensing instruments that detect radiation emitted from Earth's surface. The long-wave infrared (LWIR, 7-12 micron) and mid-wave infrared (MWIR, 3-5 micron) constitute the thermal region of the electromagnetic spectrum, and are used to measure Earth's land and sea surface temperature, as well as detect forest fires or other features that are warmer than their surroundings.

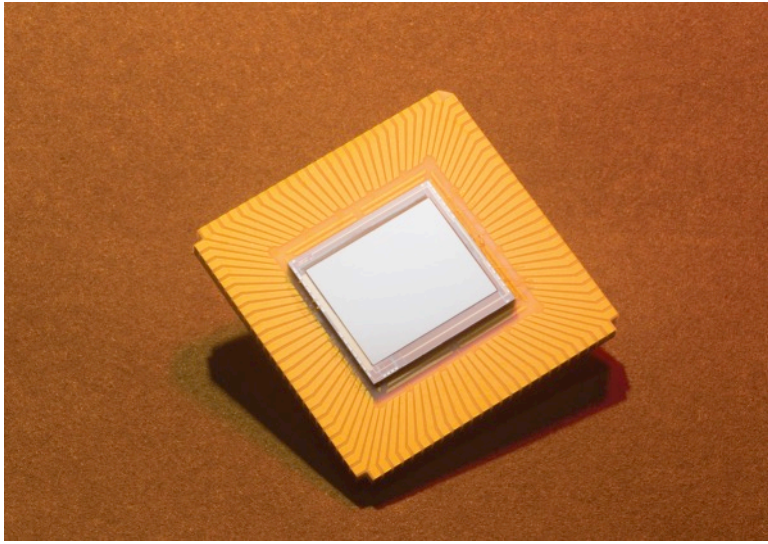
The detectors found in these instruments need to be operated at very cold temperatures — as low as 50 Kelvin — to reduce “noise” from other sources and to deliver stable measurement performance. But the hardware needed for this extreme cooling adds a cost to the overall satellite mission in terms of power, volume, and mass, and prevents infrared instruments from being flown on smaller platforms such as CubeSats.

A project led by Sarath Gunapala at the Jet Propulsion Laboratory is exploring several component-level technologies that could enable LWIR and MWIR focal plane arrays (FPAs) with significantly higher operating temperatures, requiring only a simple, small single-stage cooler.

How Hot is HOT BIRD?

Creating IR detectors is an incredibly tricky process that requires powerful machines, state-of-the-art nano-fabrication tools, and a high degree of skill—all of which make it a very expensive undertaking. In addition, these arrays must be operated at very low temperatures, which requires extensive cryo-cooling. Therefore, lowering the manufacturing costs and raising the operating temperatures of these sensors are both highly desirable.

Currently, most infrared photodetectors are made from mercury cadmium telluride (HgCdTe). Over the past two decades, much effort has gone into the search for lower-cost alternatives to this material. Indium antimonide (InSb) is one alternative, although it requires much lower operating temperatures and does not have an adjustable cutoff wavelength like HgCdTe (the cutoff wavelength is the longest infrared wavelength that can be detected effectively). InSb, however, is a very robust material, which means that InSb detectors can be much more cost-effective to make.



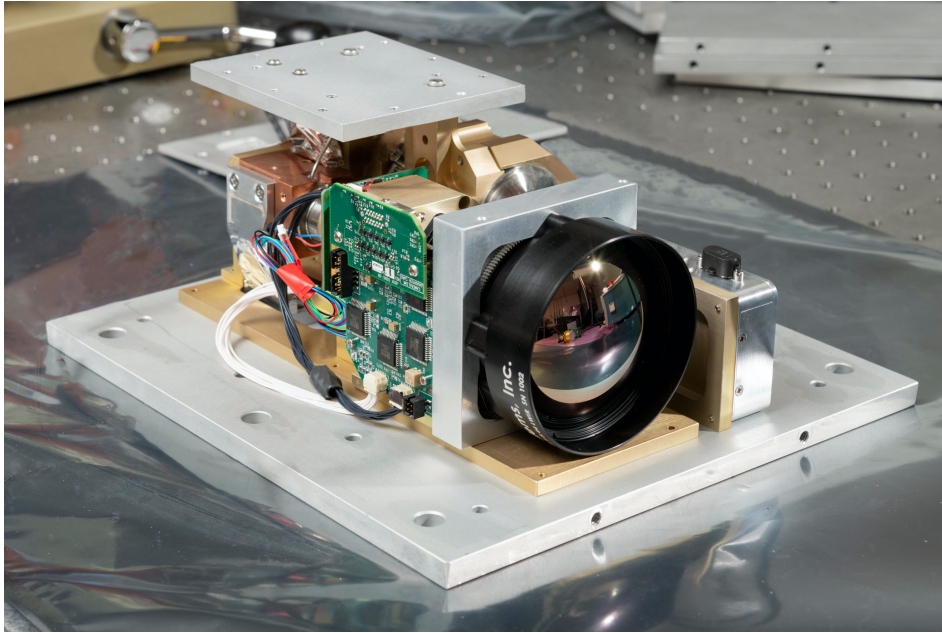
A 640 x 512 pixel LWIR focal plane array. Credit: Sarath Gunapala/JPL

HOT BIRD detectors combine the higher operating temperature characteristics of HgCdTe with the material robustness manufacturing advantages of InSb. In addition, the HOT BIRD detectors offer continuous cutoff wavelength adjustability similar to HgCdTe detectors, enabling them for use in multiple applications.

The HOT BIRD team has developed a unique process to create the focal plane arrays that enable these sensors. Using carefully chosen elements and alloys of elements, atoms are deposited onto a special substrate material, coaxed into orderly rows, and then 'grown' into three-dimensional crystalline structures called superlattices. After more processing, these artificially created superlattices are fabricated into the BIRD focal plane arrays. Almost every aspect of the process can be customized, or tuned, to achieve specific results or measure a particular infrared wavelength. A versatile and reliable technology like HOT BIRD expands the options for scientists and researchers, allowing them to choose the best tool for the desired application.

This BIRD is poised to fly

A HOT BIRD detector will soon be launched as part of the Hyperspectral Thermal Imager (HyTI)—an instrument technology demonstration funded by NASA's Earth Science Technology Office (ESTO) under the In-Space Verification of Earth Science Technology (InVEST) program. The HyTI payload is designed to fit in a 6U CubeSat planned for low-Earth orbit (LEO). An LWIR HOT BIRD will serve as the detector for HyTI's FPA. The HyTI mission's objective is to obtain important spatial, spectral, and temporal information on hydrological dynamics and land surface temperature. This information can be used for water resource management for agricultural applications.



HyTI instrument on the instrument test bed. HyTI FPAs are being developed by Drs. Sarath Gunapala, Sir (Don) Rafol, David Ting, Alexander Soibel, Brian Pepper, Arezou Khoshakhlagh, and Cory Hill at the NASA Jet Propulsion Laboratory, California Institute of Technology . HyTI is a joint project in collaboration with Drs. Robert Wright, Paul Lucey, and Luke Flynn at the University of Hawaii; Dr. Miguel Nunes at the Hawaii Space Flight Laboratory; and Dr. Tom George at SaraniaSat, Inc. The NASA InVEST program awarded the HyTI proposal in 2018 and selected it in 2019 to fly in late 2021 or later as part of its CubeSat Launch Initiative.

Scientists are actively engaged in developing infrared Earth and planetary imaging applications supported by the NASA Research Opportunities in Space and Earth Science (ROSES), Advanced Component Technology (ACT) and Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) programs. HOT BIRD sensors could potentially be used in NASA space flight projects as well as airborne, balloon, ground based, and in situ instruments to support research in many areas, such as:

- Fire detection
 - Seeing where flames are active despite haze or smoke
 - Identifying dangerous hot spots that are not visible to the eye
- Imaging land forms on Earth, the Moon, other planets
 - Material detection, identification, and measurement
 - Monitoring geologic processes, in situ resources
 - Monitoring agriculture crops for moisture, nitrogen, chlorophyll, sugars—i.e., are the crops healthy and growing as desired?
 - Finding snow and ice
- Atmospheric sounding

- Mapping contamination and hazards (e.g., Superfund sites, oil spills, methane leaks)
 - Ecosystem composition and modeling (measuring ozone, CO₂, H₂O, etc.)
 - Enhanced weather detection and prediction (ocean surface temperatures, etc.)
- Atmospheric correction—the ability to see through dust, clouds, haze, etc. (important for safely landing aircraft or helicopters)
- Detecting the presence of electromagnetic radiation (EMR), gravitational fields, magnetic fields, seismic waves, acoustic waves, and other phenomena
- Addressing key science questions related to habitability

Biological and Physical Sciences



Apollo 17 Astronaut Harrison "Jack" Schmitt coated by lunar dust during his field investigation (left). University of Colorado Boulder/NASA Solar System Exploration Research Virtual Institute (SSERVI) lab set up to demonstrate the new electron beam technology (right).

Project: Lunar Dust Research and Mitigation

Sponsoring Organizations:

Biological and Physical Science Division,
Planetary Science Division, SSERVI/Institute
for Modeling Plasma, Atmospheres and
Cosmic Dust (IMPACT), Space Technology
Mission Directorate

Project Leads: Drs. Inseob Hahn (NASA/Jet
Propulsion Laboratory, California Institute of
Technology), Xu Wang (Colorado University,
Boulder)

Snapshot: To help protect future space assets
and astronauts from dangerous effects that
arise from Moon/Mars dust exposure, NASA is
developing a new technology that will utilize
electron beams/ultraviolet light to remove
dust.

Key terms: Dust mitigation, Electrostatic dust
charging, Lunar surface exploration, Electron
beam

New "Moon Duster" Will Help Clean NASA Assets in Space

The Apollo missions faced a high risk of dust-related damage to space hardware and astronaut health. Fortunately, NASA researchers have recently determined that lunar dust can be zapped away using a beam of electrons. NASA is exploring use of non-contact, electrostatic, dust-charging technology to protect the Agency's important space assets without restricting mission parameters.

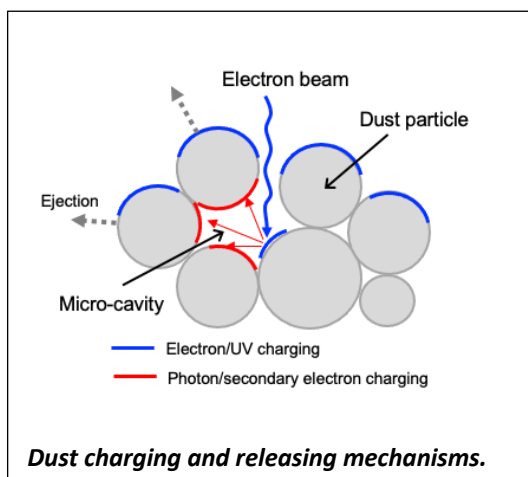
The lunar surface is covered by a layer of dust particles called regolith. These dust particles can be stirred up during robotic and human exploration activities or released by natural processes such as meteorite impacts. Apollo astronauts noted that lunar dust particles readily stuck to surfaces such as spacesuits, optical lenses, and thermal blankets, causing numerous problems. Apollo mission spacesuits were damaged by abrasive lunar dust and several

astronauts noted that moon dust was resistant to cleaning efforts; even vigorous brushing could not remove it.

NASA's Artemis program will develop extensive resources on the Moon starting in 2024 and will require advanced technologies to enable a sustained lunar presence. Mitigation of lunar dust adhesion will be central to these efforts and to Artemis's success. However, lunar dust exhibits several characteristics that make it difficult to remove. For example, unlike Earth, the Moon does not have an atmosphere and magnetic field to protect its surface from solar radiation. The solar wind can electrically charge dust particles on the Moon, causing the charged particles to stick to each other and to other surfaces. In addition, lunar dust particles are very jagged and rough, which also increases their "sticking power."

A team at NASA/Jet Propulsion Laboratory (JPL) and Colorado University (CU), Boulder is developing new electron beam technology and a tool called a "Moon duster," which can be used to remove dust on sensitive surfaces of hardware and spacesuits on the Moon. Unlike other technologies that require incorporating a complex design of active embedded layers on the surface to be cleaned, the Moon duster is a standalone, hand-held electron beam device that can be potentially used on any dust-covered space hardware on the Moon. "The Moon duster will be like a typical duster spray on your desk, but it operates without air," imagined Dr. Inseob Hahn, a program technologist and the project lead at NASA/JPL.

This new electron-beam technology is based on insights gained from previous studies of the natural electrostatic dust lofting process that may occur spontaneously on the surface of airless bodies (e.g., the Moon and asteroids). The model developed to explain this dust lofting process is depicted below. When an electron beam or UV field is applied to a micro-cavity formed in a pile of dust, the induced secondary electrons or photoelectrons are collected by the surrounding dust particles, resulting in a substantial negative charge buildup on the dust particles' surfaces. The repulsive force between these negatively charged dust particles ejects them off the surface.



To test the electron beam concept, the researchers at CU Boulder loaded a vacuum chamber with various materials coated with a NASA-manufactured "lunar simulant" designed to resemble Moon dust. After aiming an electron beam at the particles, the dust jumped off the material's surface, usually in just a few minutes, as captured in the image below. The technique worked on a wide range of surfaces, including spacesuit fabric, glass, and solar panels. This new technology aims at cleaning the finest dust

particles, which are difficult to remove using tools like a brush. The method removed an average of about 75-85% of the dust particles on the surfaces tested. The researchers are also experimenting with new ways to increase the cleaning efficiency of the electron beam. The research results are very encouraging, and now the team is developing a testbed at NASA/JPL to evaluate how the technology will perform in the very cold Moon environment. Other team members conducting this research include Benjamin Farr, who completed the work as an undergraduate student in physics at CU Boulder, and Drs. Mihály Horányi at CU Boulder, John Goree of the University of Iowa, and Ulf Israelsson at NASA/JPL.

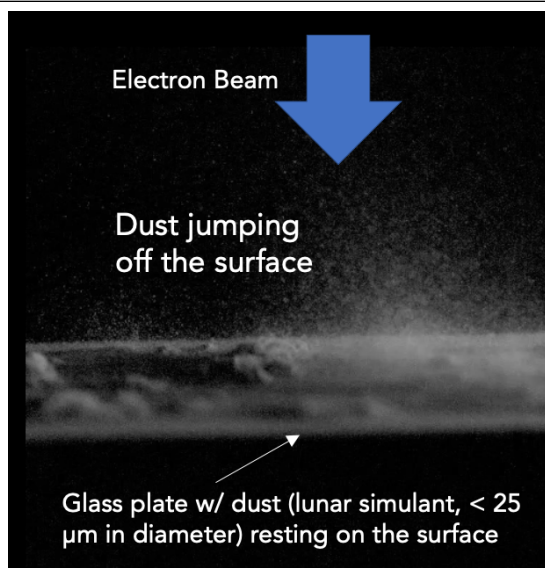
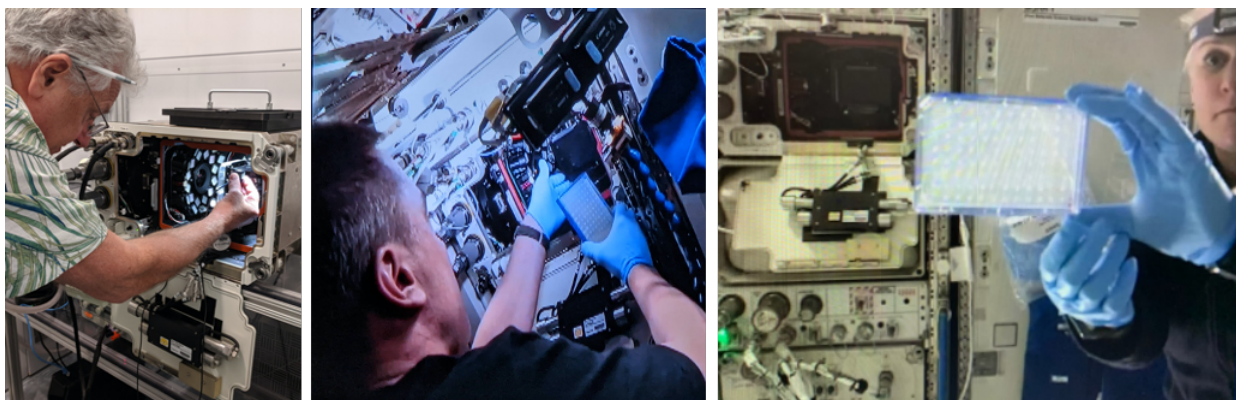


Image of dust lofting as a result of electron beam exposure.



Left: *Spectrum Engineer Dr. Scott Shipley. Center:* *Astronaut Chris Cassidy inserting specimen plate into Spectrum on ISS. Right:* *Astronaut Kate Rubins removing a specimen plate from Spectrum on ISS.*

Multi-Spectral Fluorescence Imaging System for Studying Gene Expression on ISS

Project: Multi-Spectral Fluorescence Imaging System (Spectrum)

Sponsoring Organization: Biological and Physical Science Division's Space Biology Program

Project Lead: David Flowers, NASA Kennedy Space Center

Snapshot: NASA seeks to understand the impact of the spaceflight environment on organisms in preparation for long-duration missions. Spectrum was developed to undertake these types of studies using model organisms on ISS.

Key terms: Spectrum, model organisms, gene expression, fluorescent imaging, ISS life science research.

All organisms exposed to the spaceflight environment exhibit changes in the expression of many genes relative to the comparable ground controls left on Earth. The Multi-Spectral Fluorescence Imaging System (Spectrum) enables scientists to monitor these changes in real time, non-destructively, using live organisms (plants, bacteria, fungi, small invertebrates).

While the expression of some genes does not change in the space environment, some are turned on to a greater extent and others to a lesser extent. Understanding why this happens has great implications for both long-duration space missions and achieving a better understanding of the basic mechanisms at work within life on Earth. For example, some of the genes with altered responses in spaceflight trigger plant defense responses on Earth that are normally activated by pathogens and herbivores.

NASA's Kennedy Space Center Payload Development team has developed a single-locker-sized instrument (Spectrum) that facilitates the evaluation of these phenomena (and others) in an automated fashion and requires minimal crew time.

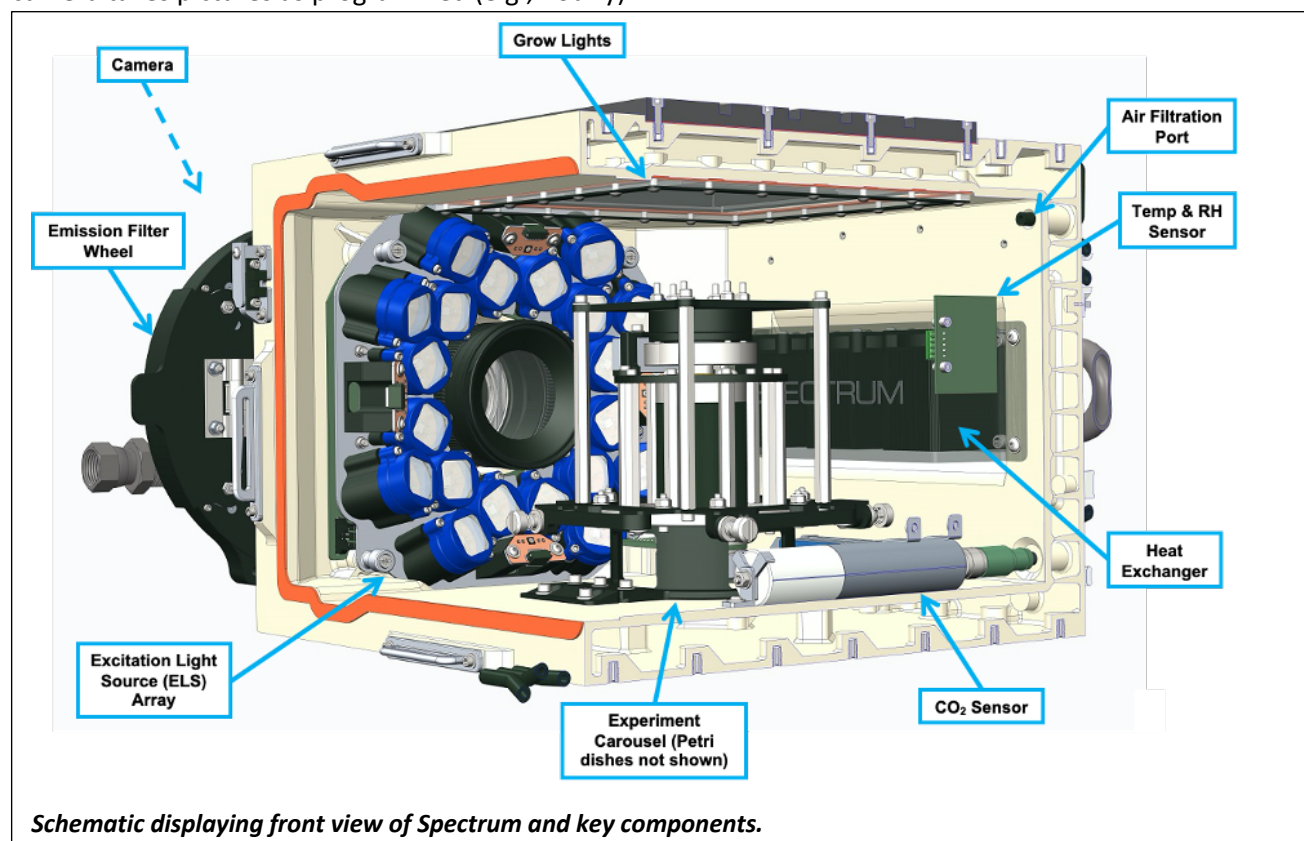
Spectrum is a multi-spectral fluorescence imaging system designed for capturing *in vivo* (i.e., within a living organism) gene expression in the low- to zero-gravity environment of the International Space Station (ISS). To

enable the detection of gene expression, DNA segments encoding fluorescent proteins are inserted into the organism's genome next to the genes of interest, so that when these genes are

activated, the fluorescent proteins are produced as well. The detection and monitoring of these fluorescent proteins will allow the scientific community to further understand biological responses of these organisms when subjected to space environments.

Spectrum resides within an EXpedite the PROcessing of Experiments for Space Station (EXPRESS) rack, which provides power, data, and other elements needed to run science experiments on the ISS.

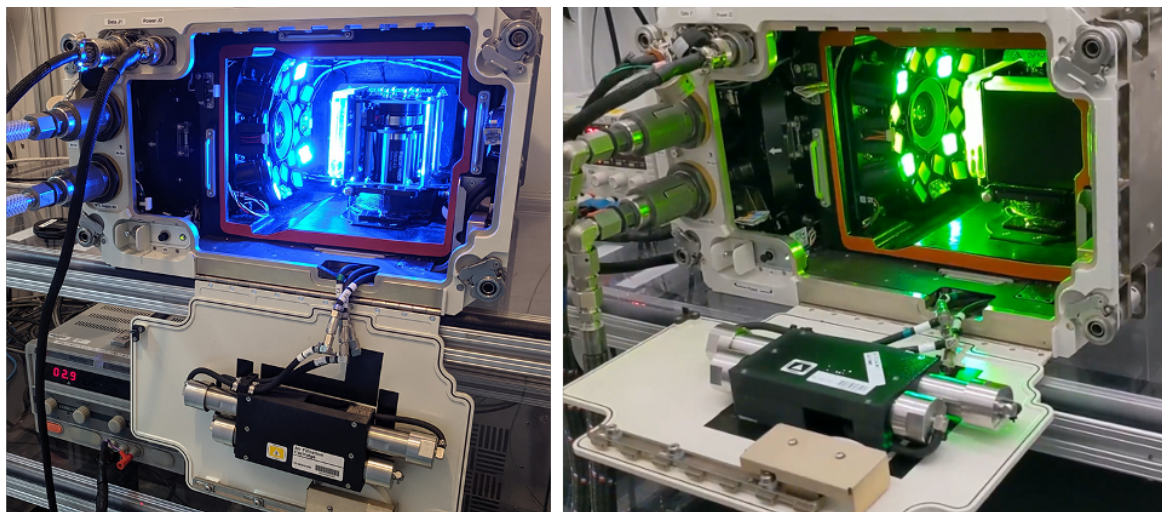
To hold the biological samples that will be observed, Spectrum accommodates standard 100 mm x 100 mm Petri plates, 128 mm x 82 mm multi-well culture plates, and other custom containers within its growth and imaging chamber. Principal Investigators (PIs) can specify automated management of chamber properties and the collection of chamber environment information, including near real-time 71-megapixel images of fluorescent emission from biological organisms under highly uniform illumination. PIs can control the Spectrum chamber temperature (18-37° C), relative humidity (RH), carbon dioxide concentrations (ranging between 400 ppm up to ISS-ambient levels), and growth light characteristics. Spectrum can also remove volatile organic compounds (including ethylene down to 25 ppb) from the environment. The Spectrum software is completely controlled via ground commanding and PIs can modify the Spectrum conditions during experiments. In a typical experiment, an astronaut loads an experimental plate with the organisms to be studied into the Spectrum unit; the system runs automatically controlling temperature and changing the lights according to a desired program; and the camera takes pictures as programmed (e.g., hourly).



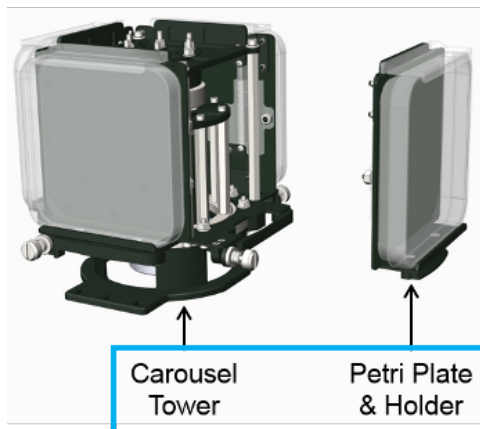
Researchers can image up to five genes at a time using a variety of fluorescent proteins that indicate genes of interest, and excitation light and emission filters that are easily replaceable on-orbit by the crew. Spectrum is also equipped with chlorophyll fluorescence imaging to monitor plant health during experiments.

Spectrum's filter wheel can hold ten emission filters and rapidly switch between them. The Excitation Light Source (ELS) uses diffusers to achieve an 80% uniform illumination of the plates containing the biological samples. Additional filters are provided to support color and infrared images. This ability to switch between emission filters allows researchers to image several fluorescent proteins in a single specimen.

Four specimen plates can be mounted and rotated for sequential imaging. Chamber air is ducted through the carousel to suppress condensation on the inside of Petri plate covers. The carousel is capable of continuous rotation up to 33 rpm and is removable to allow future modification for partial gravity exposures on-orbit.



Spectrum showing blue excitation light-emitting diodes (LEDs) (left) and green excitation LEDs (right).



Spectrum's Carousel (left) and one of four plate holders (right) removed for insertion or replacement.

To enable growth of photosynthetic organisms, a top-mounted LED light cap is equipped with broad-spectrum white (400-750 nm), red (630-660 nm), blue (400-500 nm), and green (520-530 nm) LEDs with an intensity range of 0-1000 micromoles.

Spectrum is commanded from the ground and internally collects and stores time-stamped images with the option to downlink images and chamber environmental data for near-real time evaluation by the investigator team. To accommodate new science requirements, PIs may consider modifications to certain Spectrum components including the ELS, the Emission Filters, camera lenses, chamber sensors, carousel assemblies, and the Air Filter Cartridge. Spectrum software can also be

modified during flight.

Spectrum is now available for experiments on ISS, creating a new capability for multiple types of investigations that will further NASA's goals relating to understanding the effects of spaceflight on biological organisms.

