National Aeronautics and Space Administration

Cutting edge

Goddard's Emerging Technologies

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ORCAS

An Orbiting Beacon for Ground-Based Telescopes

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Orbiting Artificial Star Could Transform Ground-Based Observatories

An artificial star can be better than a real star for an observatory peering up through Earth's blustery atmosphere. Orbiting Earth, it can be placed in the right part of the sky and tuned to the specific wavelengths of visible and near-infrared light needed on the ground.

A NASA beacon technology under development at Goddard would beam combinations of lasers down to Earth to help ground-based observatories correct for the haze, particulates, and shifting thermal layers of Earth's atmospheric lens.

"We can overcome atmospheric effects to a greater degree if we have a source in space to help us calibrate and overcome those observatories' limitations," Goddard researcher Eliad Peretz (photo right) said. "These ground-based observatories could provide space-like quality in their observations, at least in visible and near-infrared light."

Peretz is developing the Orbiting Configurable Artificial Star, or ORCAS, a SmallSat spacecraft with a laser payload smaller than a briefcase.

Image credit: Jon Reis

in this issue:

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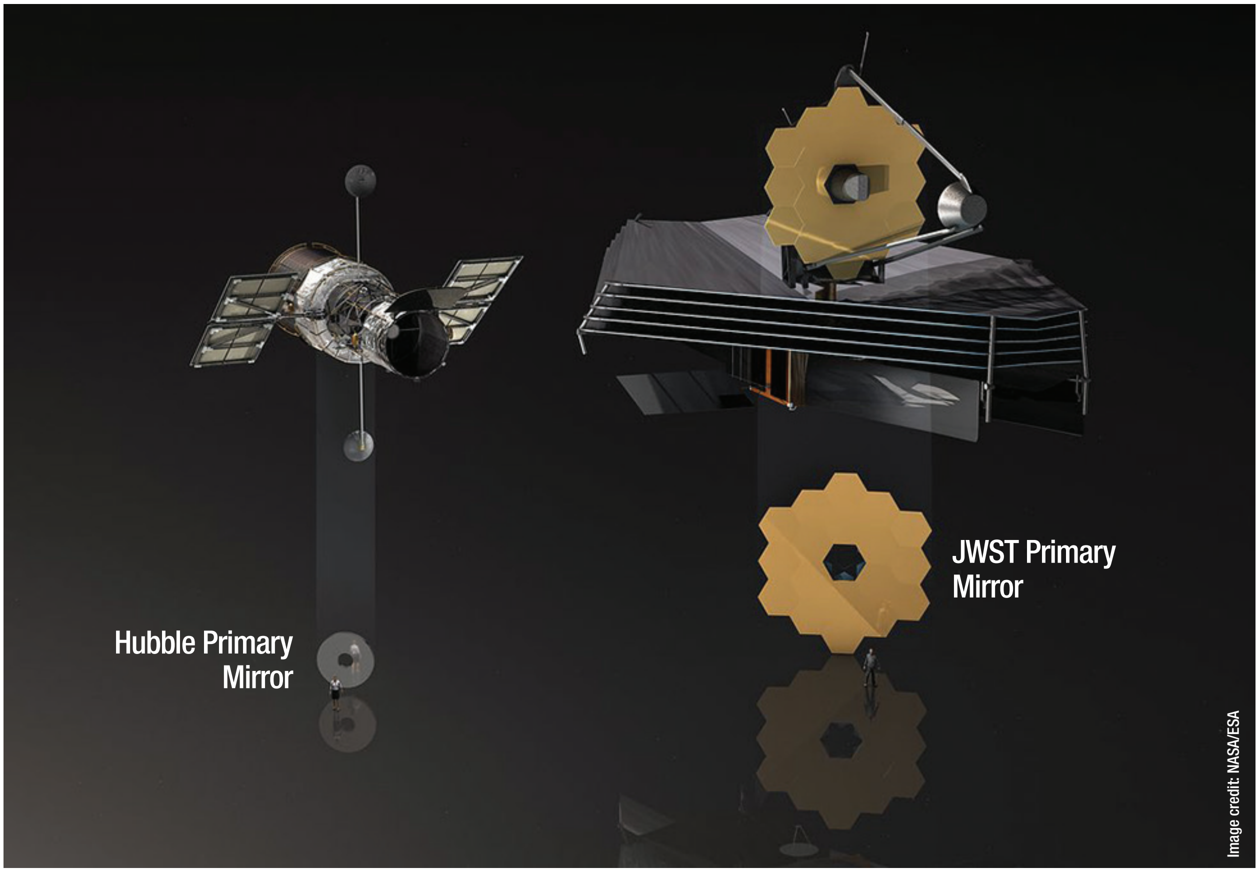
About the Cover

Goddard researcher Eliad Peretz is developing a multi-spectral, adjustable laser beacon to provide a focal point for improving ground-based astronomical observations. The Orbiting Configurable Artificial Star, or ORCAS, beacons could help current and future large-mirror observatories on the ground to tune out the haze, dust, and shifting thermal layers of Earth's atmosphere more effectively than current methods. This illustration shows a SmallSat spacecraft designed by a potential commercial supplier providing a beacon for the W.M. Keck Observatory in Hawaii.

(Image Credit: NASA/ISS/Eliad Peretz/ESO/S. Brunier/BCT)



A reflecting telescope's resolution is ultimately decided by the size of its primary mirror.

Many ORCAS beacons could fly in a variety of orbits to serve different purposes and users.

Why do astronomers need them?

Orbiting observatories like the Hubble Space Telescope give us dazzling views of astronomical objects by orbiting above the atmosphere. However, in astronomy, bigger is better, and space telescopes have limitations on the size of the primary mirror that can be launched into orbit. Hubble has a 2.4-meter primary mirror, while the James Webb Space Telescope's 6.5-meter, compound mirror had to fold up into a compact launch package. Many currently operating ground-based telescopes have mirrors exceeding 8 meters, with much larger mirrors under construction.

Current image correction, or adaptive optics, technologies depend on observing a known, bright guide star in the telescope's field of view or shining a laser up through the atmosphere to create a faint artificial star. Like noise-canceling headphones but for light, sophisticated processing techniques then compare that beacon's observed signal against its known qualities to measure and cancel out distortion.

Peretz's precision-tunable ORCAS beacon improves on the state of the art in several ways. ORCAS could be positioned in the right place in the sky at the right time and tuned to deliver the wavelength and brightness needed by an individual observatory, allowing astronomers to hone their focus on the specific cosmic objects they seek to study. The beam could even be widened to serve multiple telescopes within an observatory's geographic location, such as the 13 telescopes at Mauna Kea, on Hawaii's Big Island, including both 10-meter telescopes of the W.M. Keck Observatory.

Peretz will visit the Keck Observatory this spring as part of NASA's Astrophysics Science SmallSat Studies, or AS3 program. There, astronomers will focus the telescope on an asteroid passing a celestial object to demonstrate how an orbiting ORCAS beacon might appear from the ground. "We just need an object that is bright enough to be visible near the target and crossing the sky slowly enough to fuel the adaptive optics systems," Peretz said. "We will show that the ground systems are capable of using a moving target in visible wavelengths."

Though still a mission concept, the ORCAS project enjoys strong support in the astrophysics community, including Goddard Nobel Laureate Dr. John Mather.

"With Keck, we could get four times better resolution than Hubble has in space," Mather said. "We could see fine details of distant galaxies or the heart on Pluto, and we could measure the expansion rate of the universe a bit better."

He added, "the most exciting possible benefit would be new observation capabilities for exoplanets. Astronomers are already working on extreme adaptive optics solutions for this, but the idea only works well for very bright stars. A laser beacon could make it work for all stars. If this works as we think, every observatory will want to use the beacons."

Staring at the Sun

Closer to home, ORCAS could help answer fundamental questions about how the Sun's corona is heated, how it provides mass to coronal mass ejections and the solar wind, and how solar flares take place, Goddard astrophysicist Doug Rabin said. Larger collecting mirrors and higher-resolution imaging are key to observing these processes, along with other tools being developed. The physics behind them have been studied extensively with advanced computer models of solar activity, but the difficulty of resolving fine details of structures and activities in the Sun's inner corona remains a challenge ORCAS and other technologies are racing to overcome.

"What we're looking for would be in the tens of milliarcseconds across," Rabin said. "That means it would appear smaller than a half dollar coin atop the Empire State Building, viewed from New Haven, Connecticut. Your angular resolution, your ability to see those tiny but crucial details, goes up as your telescope diameter increases."

Peretz and Rabin are working with the National Solar Observatory's brand-new Daniel K. Inouye Solar Telescope (DKIST): a 4-meter telescope being commissioned at the Haleakala Observatory on the Hawaiian island of Maui. Funded by Goddard's Internal Research and Development, or IRAD program, they will test ORCAS's benefits for ground-based solar observations using a similar test as at Keck.

DKIST has already obtained stunning high-resolution images of the Sun's disk, Rabin said. With an assist from ORCAS, the telescope will get scientists an improved view into these processes.

"DKIST is big, so it could be capable of resolving very tiny coronal features, as small as 30 milliarcseconds, in the corona," he said, "but it can't do it right now. Its adaptive optics system works beautifully on the disk of the Sun, but it doesn't work in the corona because there's not enough contrast to lock in on a target, and that's where ORCAS comes in."

On August 22, Regulus could provide the beacon DKIST needs to resolve details in the corona, as well as prove the value of the ORCAS concept. While Regulus is only available once a year, the artificial star could perform the same role year-round, Rabin said, providing a bright "star" where and when needed and adding many more opportunities to observe the inner corona. ❖

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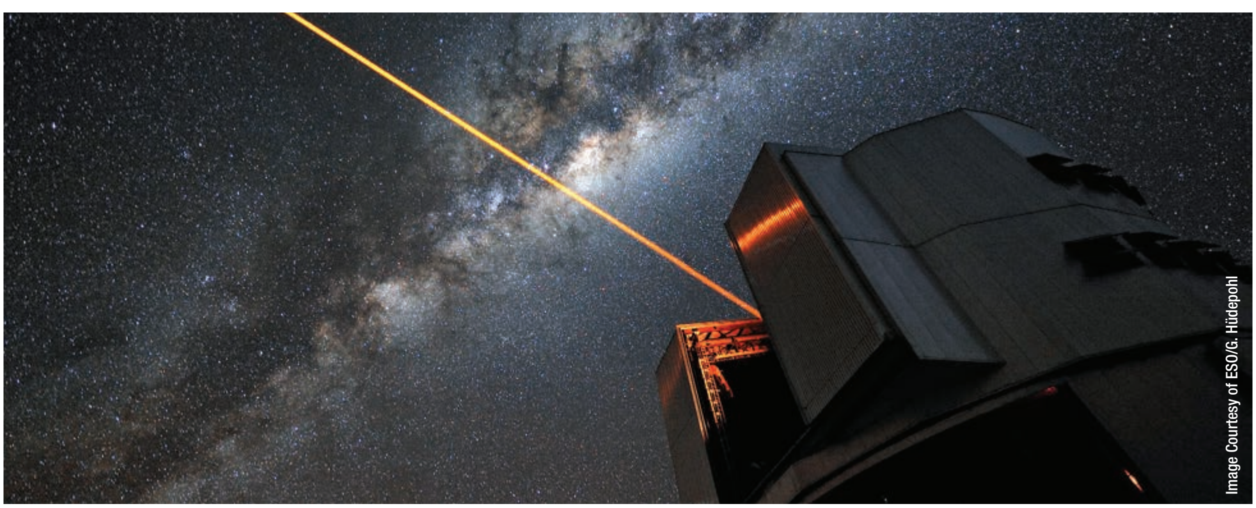


Image Courtesy of ESO/G. Hüdepohl

The European Southern Observatory's Very Large Telescope uses a laser guide star beacon to help cancel out disturbance caused by Earth's blustery atmosphere.

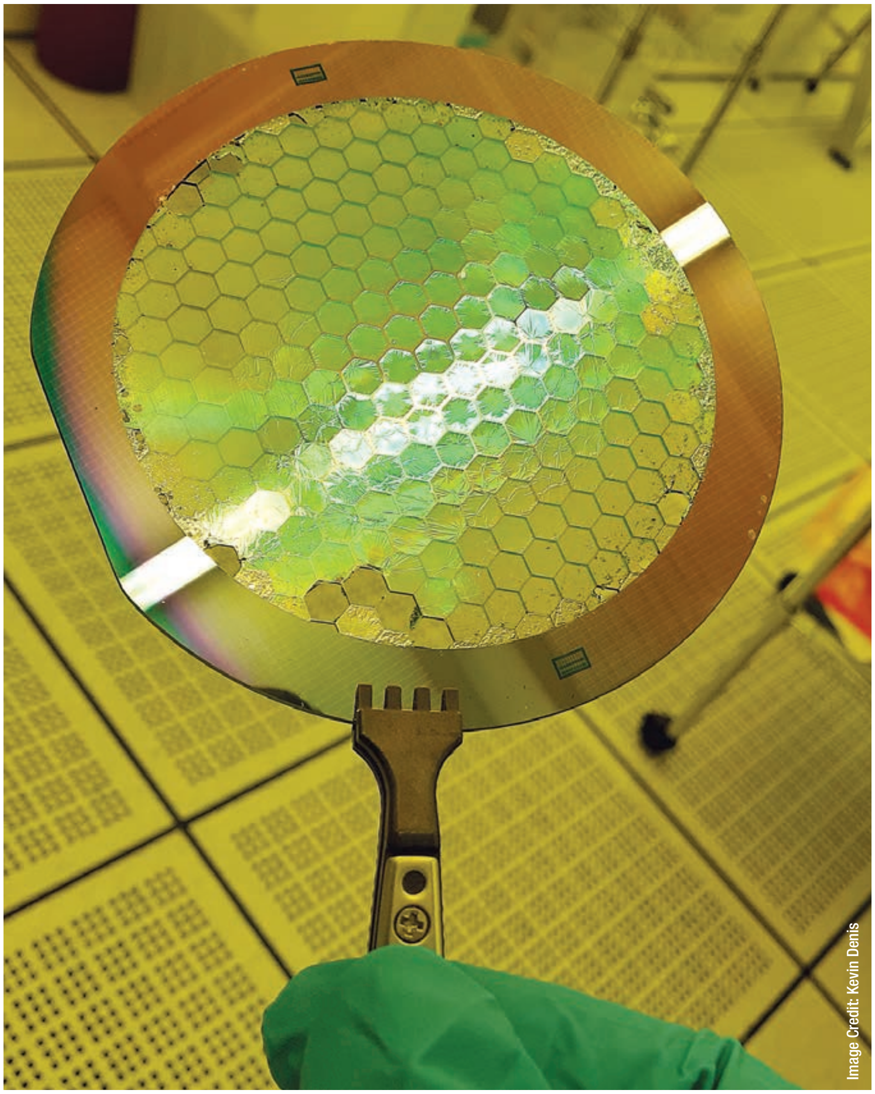
Photon Sieves Advance Toward a Solar Observatory Concept

To better understand the Sun's behavior, scientists want to observe very small processes close to the surface that emit light in extreme ultraviolet wavelengths – 10 times shorter than the wavelengths of visible light.

Imaging in extreme ultraviolet, or EUV light, hasn't been done at the level of detail needed to distinguish these processes, which have been inferred through advanced computer models. This is because conventional lenses block EUV light, and EUV mirrors cannot be polished accurately enough for them to achieve the ultimate resolution of tiny features.

To explore this blind spot, Goddard researchers say thin-film photon sieves, which diffract EUV light to a focal point, could provide 10- to 20-times greater resolution than the images of the Sun captured by the Solar Dynamics Observatory. Viewing these processes in motion could answer significant questions about the nature of our star, how the Sun's upper atmosphere is heated, the origins of flares and coronal mass ejections, and the space weather these solar eruptions create throughout the solar system.

"It's about unlocking the clues to what causes the Sun's corona to be energized," Goddard physicist Adrian Daw said, "and of course that's what drives space weather."



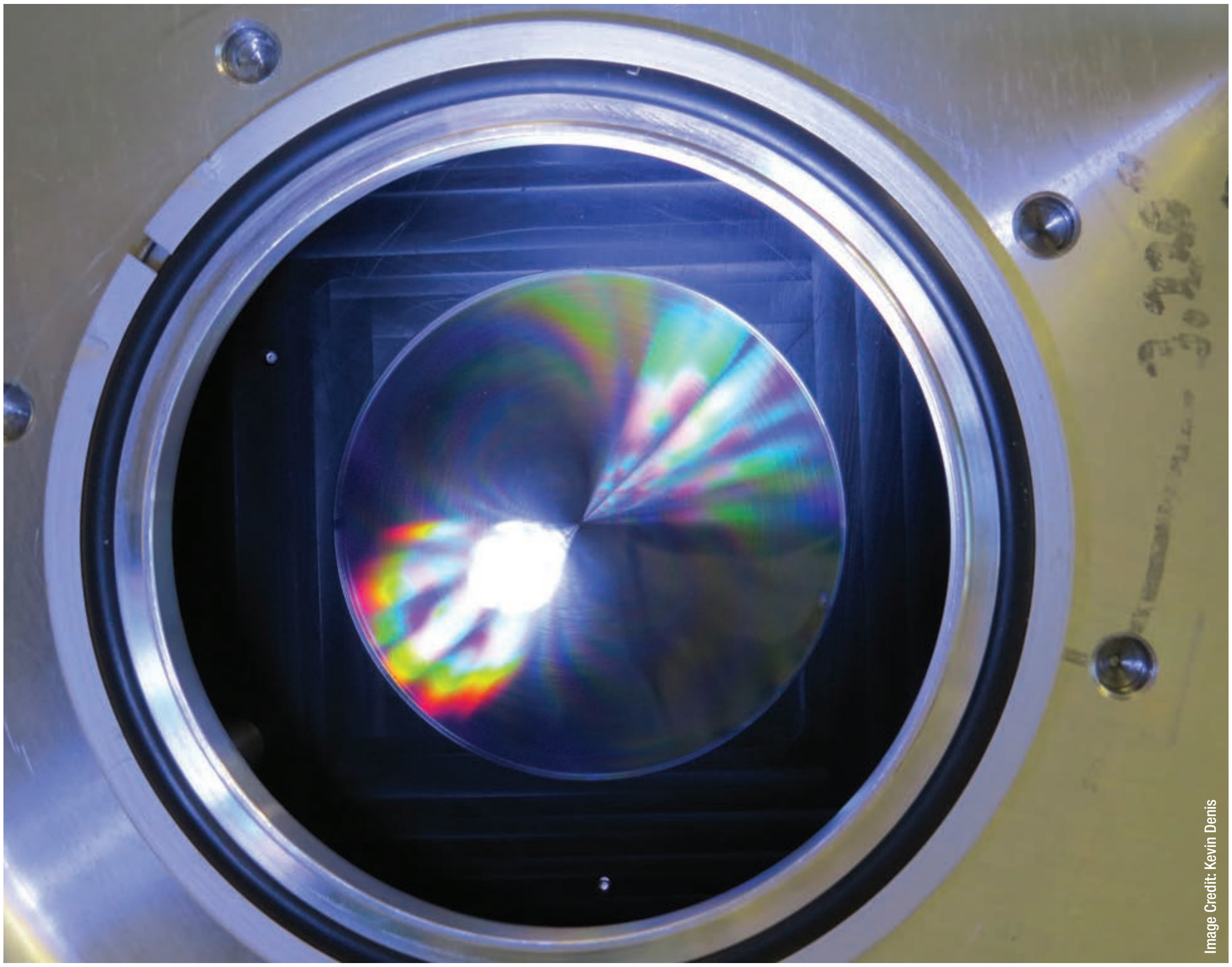
Pioneering work in thin-film photon sieves like the one above, produced by Goddard's Kevin Denis, promise to someday deliver high-resolution, extreme ultraviolet images of the solar corona.

Daw is working with a Goddard team including scientists Anne-Marie Novo-Gradac and Doug Rabin and engineers Kevin Denis and Meng Ping Chang. Someday, they hope to achieve milliarcsecond resolution in the EUV spectrum to observe these processes. This would be like being able to see a city the size of Los Angeles on the surface of the Sun.

"SDO's cameras are able to image small solar flares down to the arcsecond level," Daw said. "A photon sieve could achieve 0.05-arcsecond resolution, or 50 milliarcseconds, in its current version."

Proving the Tech

While still perfecting larger and finer sieves for a future solar observatory mission concept, the team has used their progress to calibrate the sensors of several sounding rocket missions. These include the Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS) mission, which measured ionized elements in the Sun's atmosphere by separating the



Engineer Kevin Denis created this photon sieve used to calibrate the instruments of the Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS) mission.

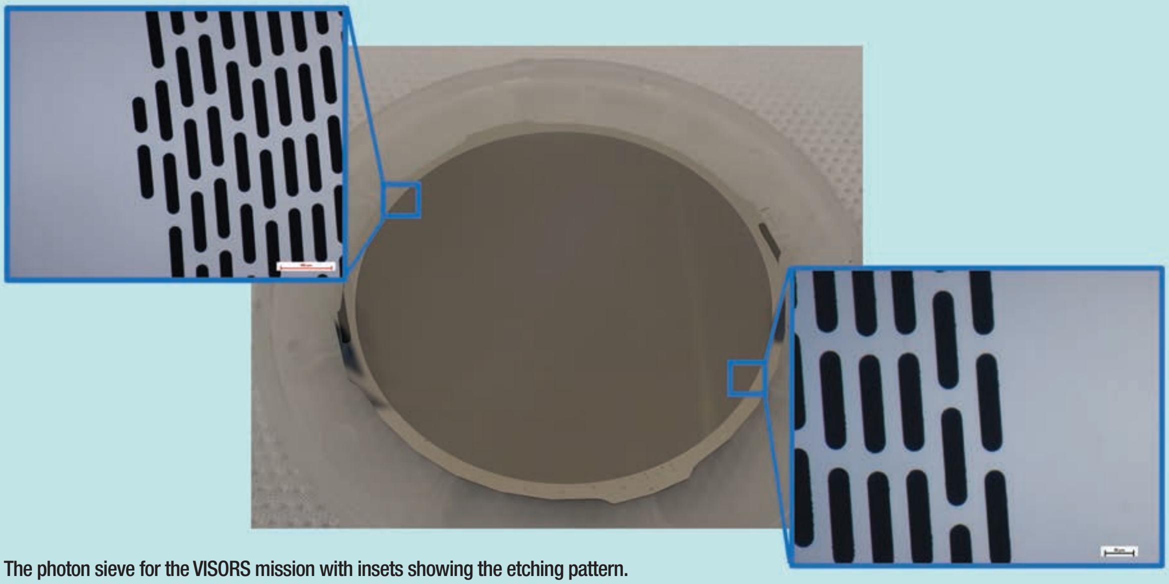
EUV light wavelengths emitted by different atoms and ions at extremely high temperatures.

The sieve team is also serving as co-investigators on the Multi-slit Solar Explorer (MUSE) mission, selected as a NASA Heliophysics MIDEX this February. There they will again use sieves to calibrate the mission's EUV sensor, a multi-slit spectrometer which is an advancement of EUNIS's instrument. MUSE seeks to obtain the highest-resolution measurements ever captured of the solar corona and transition region, where the Sun's lower atmosphere interacts with the much hotter corona above.

To fully realize the value of the sieves in space, however, the team needs a formation-flying telescope system to make use of the long focal length they provide. Their opportunity came in the form of a National Science Foundation project managed by the University of Illinois at Urbana-Champaign. The Virtual Super-Resolution Optics with Reconfigurable Swarms (VISORS) experiment will employ two CubeSats using a Goddard sieve as a diffracting lens. The lead spacecraft will hold the sieve while its solar panels serve as a sunshade for the sensor spacecraft that will collect the focused EUV light.

Photon sieves are usually created by precisely etching millions of holes through an EUV-blocking membrane. The light waves that diffract through the holes interact to create a focus at a distance from the sieve. The holes start at 143 microns in diameter (just over 0.1 mm) near the center and narrow down to 2 microns in diameter in the outer rings of the film.

To observe the Sun, Denis has been pioneering larger and larger sieves on thinner films. His team is currently perfecting 170-mm diameter sieves that could power a telescope like VISORS. The films are just 25 microns thick. In parallel the team is perfecting techniques to significantly increase efficiency by reducing the membrane thickness to under a micron so that it will transmit EUV light. The membrane thickness and material are chosen to help focus the light.



The photon sieve for the VISORS mission with insets showing the etching pattern.

Traditional sieves create a sharp image but aren't very efficient—too much of the light is lost along the way. To address this shortcoming, Denis has fabricated ultra-thin structured polymer films that can direct much more of the light to the focus. The thin films support a variant of the Fresnel zone plate, an older type of lens originally patterned on glass which focuses light using a series of concentric rings of alternating transparent and opaque surfaces. Fresnel zone plates use diffraction, unlike standard telescopes which refract light through a lens or reflect off a mirror (see *CuttingEdge* Summer 2016, Page 18).

Denis and the team earned a patent for fabricating the ultra-thin structured polymer films.

The Bigger Picture

"VISORS will be the pathfinder for a bigger mission that we will propose in the not-too-distant future," Daw said. "We envision a multi-channel telescope, where you actually do have different sieves and detector systems to study different aspects of the Sun's inner atmosphere."

Similar to SDO's Atmospheric Imaging Assembly (AIA), which uses four telescopes to capture eight bandwidths of light, their system would incorporate up to six sieves in the lead spacecraft and six detectors on the rear spacecraft. This will allow scientists to dissect different processes within the Sun's atmosphere with sieves tailored to focus in on the EUV light wavelengths produced by different elements at different temperatures.

Distributed systems like a formation-flying observatory bring their own challenges. That is why the team is working closely with Novo-Gradac and Rabin, who are developing the precision flying and sunshade technologies to round out the observatory concept (see *CuttingEdge* Winter 2021, Page 11; and Summer 2020, Page 2). ❖

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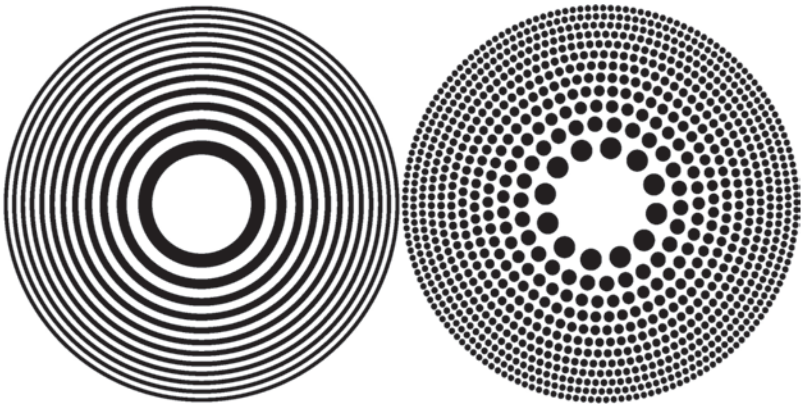

A Fresnel zone plate, left, uses diffraction to focus light to a point through progressively thinner transparent rings in a sheet of glass. A photon sieve, right, uses the same principle of diffraction to focus extreme ultraviolet light through holes etched in a silicon disk.

Image Credit: Adrian Daw

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Palm-Sized Laser with Out-of-This-World Uses

Physicist Barry Coyle and Laser Engineer Matthew Mullin show the rapid-prototyping work done in their Goddard lab to develop small, powerful lasers for planetary exploration using 3D printing and metallic electroplating. The laser prototypes held by Coyle (left) could once have filled an armature like the one held by Mullin.

A new laser in a tiny package could pin down the age of rocks on other planets. It also could fit into a small lander or an astronaut-deployed, portable chemistry lab.

The laser developed by Goddard Physicist Barry Coyle fills a gap in available technology, giving future planetary missions a powerful but compact and lightweight tool to explore how other worlds formed. Geologists use the ages of rocks to interpret how planetary surfaces formed and evolved throughout the solar system.

Coyle's laser produces a high-pulse energy beam by getting the pulse duration, or width, well below a nanosecond. In the world of solid-state lasers, shorter pulses can deliver more peak power to the target, but size reduction usually brings reduced pulse energies. This design, he said, breaks that rule.

"It also means the electrical power required to operate the laser is reduced," Coyle said. "The peak intensity needs are still met, and it fits in the palm of your hand."

In addition to shrinking the laser itself, lowering power requirements enables smaller rovers and landers to reap the benefits, he said, as well as reducing mission budgets.

Size is critical to planetary scientist Barbara Cohen, who wants to determine the age of rocks on other planets as NASA explores farther into the solar system. These won't be the large rover missions like Curiosity and Perseverance on Mars, she said. "The lasers those missions carry are too big for our applications. We're going to be looking at small samples inside a chamber. We want to be able to infuse it in planetary lander applications in a very compact package." Cohen and her team are completing a Development of Advanced Lunar Instrumentation (DALI) project to miniaturize her geochronology instrument.

Cohen uses a technique, called laser-induced breakdown spectroscopy, to measure the composition of a rock sample. The laser would separate molecules in a rock into atoms and excite them using an ultraviolet laser. A spectrometer then measures the light emitted by these energized atoms, identifying the elements that made up the rock. Cohen is particularly interested in the presence of two specific elements that reveal when rocks and minerals crystallized. "I want to measure potassium and argon," she said. "Over time, potassium decays to argon, so the abundance of those elements tells me how old the rock is."

3D Printing for Improved Delivery

The laser package Coyle and Engineer Matthew Mullin are developing for Cohen fits in a cereal bowl, including the laser and components used to tune and focus the beam. Mullin used 3D printing to quickly develop and refine individual parts of the laser.

"Being able to design and then 3D print laser parts in the same room is really exciting when work-ing on new concepts," Mullin said. "It helps you work through different laser designs faster and at significantly less cost compared to conventional machining."

The speed and freedom of designing and redesigning parts in resin helps ensure the instrument will meet science requirements before they commit to reinforcing the prints for flight.

"It also gives you a dress rehearsal for assem-bling parts, so you know what to look out for when installing the space-flight versions of the hardware," Mullin said.

Finally, they send the resin prints to an external vendor to electroplate them, making the part almost strong as machined aluminum, Coyle said. It also provides electrical and some thermal connectivity to aid in heat dissipation. Recent advances in print-

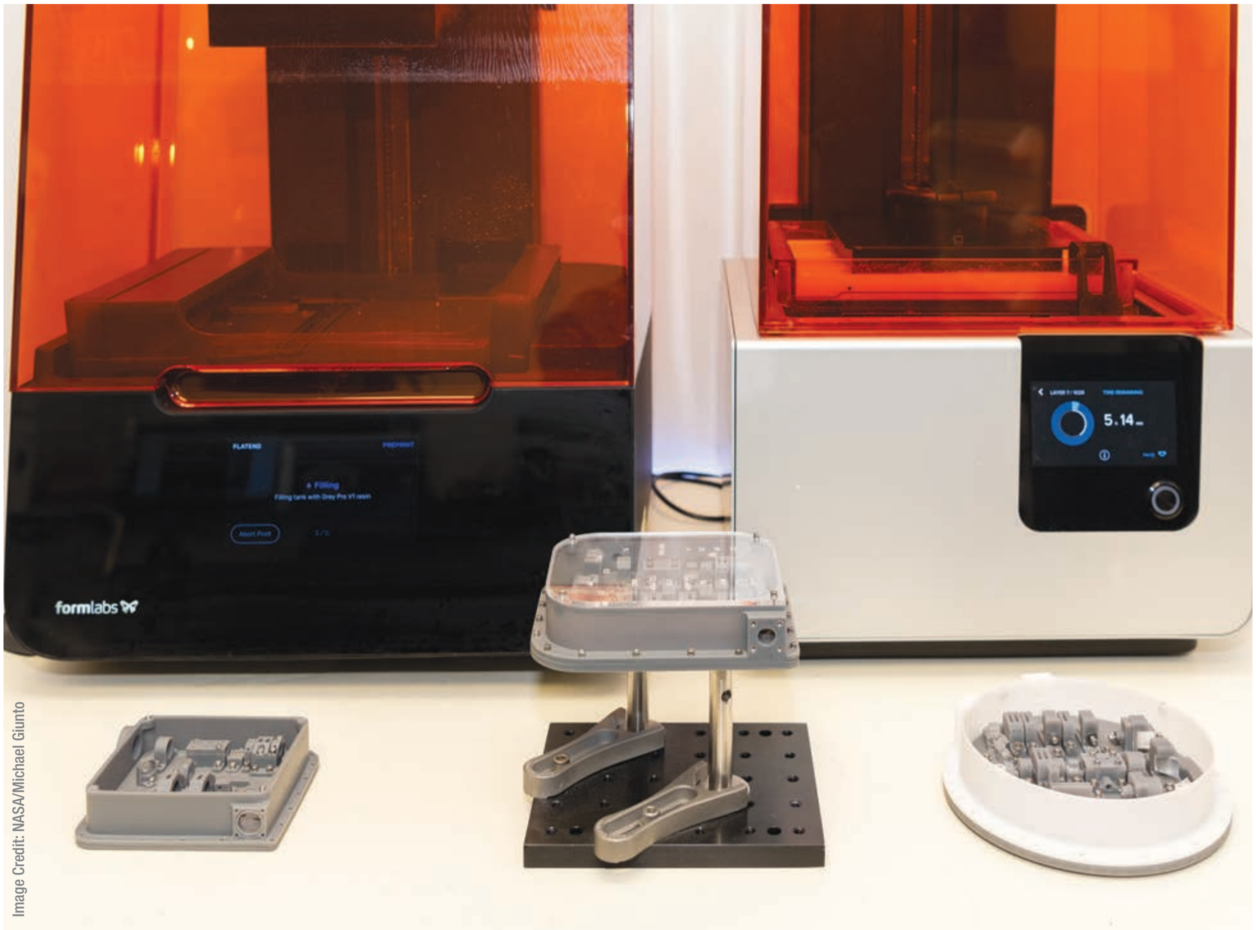

Image Credit: NASA/Michael Giunto

3D printed laser components like these were once custom milled from lightweight metals. The printing process enables Goddard innovators to prototype and test lasers to fulfill science objectives and needs at a fraction of the time and expense before committing to final, flight-ready versions.

able resin chemistry have improved critical characteristics such as strength, low thermal expansion, broader thermal capabilities, and reduced total mass. These aren't simple plastics anymore, he said.

The laser may have applications beyond planetary exploration, Coyle said, including communications, lidar, altimetry, ranging, or additional spectroscopy applications.

"I hit this rare niche with this design," Coyle said. "You can't buy a laser anywhere this size that puts out this kind of energy at this pulse width. ❖

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Goddard Laser with GEDI Heritage Bound for Titan

The Dragonfly mission to Saturn's moon Titan will benefit from more than a decade of laser technology development at Goddard.

The dual-quadcopter Dragonfly lander will land in multiple locations on the icy moon sampling the air, soil and ice looking for key organic compounds that are the building blocks of life. The Dragonfly Mass Spectrometer, or DraMS, uses an ultraviolet laser to vaporize parts of those samples before passing those particles into the mass spectrometer, where they will be identified by their molecular mass.

Goddard Laser Engineer Barry Coyle developed the laser through Goddard's Internal Research and Development (IRAD) program and will begin working on the flight version this summer. Coyle said DraMS benefited from his experience building another IRAD-funded laser innovation, the Global Ecosystems Dynamics Investigation, or GEDI lidar system. GEDI measured Earth's forest canopy from its perch aboard the International Space station.

"What we learned from that," he said, "we used on Dragonfly. We literally shrank everything by a factor of three."

Dragonfly Deputy Principal Investigator Dr. Melissa Trainer said the compact, powerful DraMS laser will allow the mission to identify the building blocks of life on Titan.

"We know there's really rich chemistry on Titan," Trainer said, "because we have seen it happening in the atmosphere. We've skimmed the atmosphere with Cassini and the descent of the Huygens probe in 2005 and measured it. Our main goal with Dragonfly is to go back and look for signs of prebiotic chemistry on the surface, where organics may have interacted with liquid water in Titan's past. The signs of life we're talking about are the types of molecules, such as amino acids and nucleobases, that life is built from."

Trainer said they would like to see large organic molecules whole, or at least preserved as much as possible.

"We can do that with the UV laser," she said. "Instead of heating up the sample, you are more directly plucking them off the surface and ionizing them. It allows these large molecules to stay mostly intact as they get analyzed by the equipment."

That analysis, she said, should help answer the basic question, "Are they just simple polymers or are they more complex combinations which we think are important for prebiotic chemistry?" ❖

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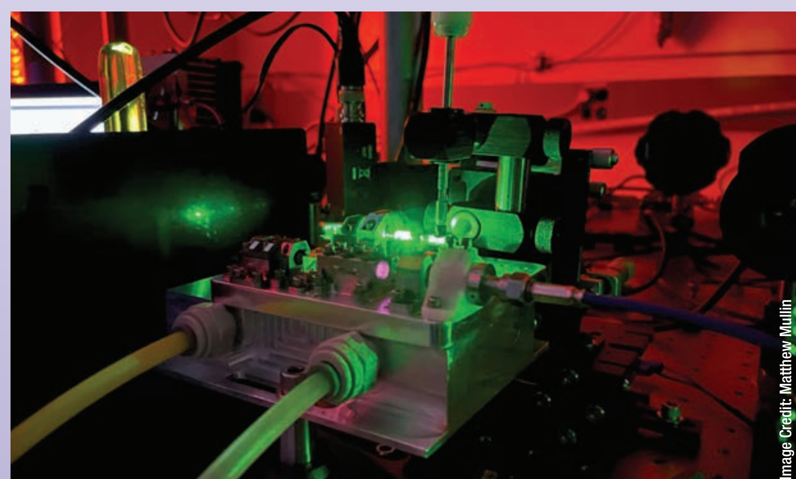
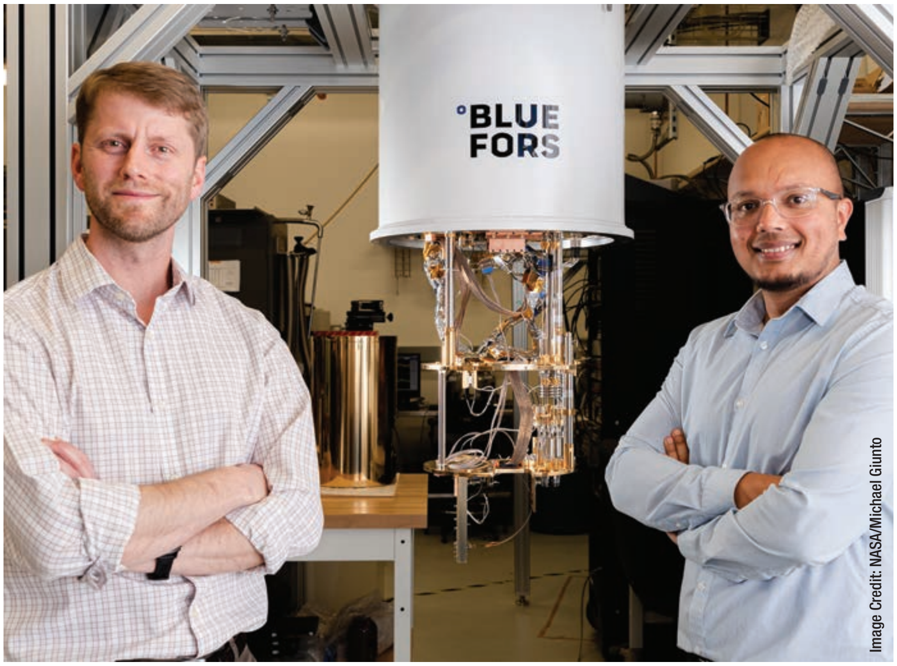


Image Credit: Matthew Mullin

A prototype of the Dragonfly Mass Spectrometer (DraMS) laser with 3D-printed parts is tested on a bench in a Goddard laser lab. The compact laser will help power a chemistry lab aboard the Dragonfly probe which will visit Saturn's moon, Titan.

Seeking the Universe's Baby Pics

Improving our imaging of the oldest light in the cosmos could reveal faint ripples of gravitational disturbances from the earliest moments of the universe.



Thomas Essinger-Hileman and Sumit Dahal developed the microwave pixel sensors suspended in this cryogenic testing facility at Goddard. Each pixel is etched into a roughly 2 by 2 cm silicon chip.

The initial discovery of this light, known as the cosmic microwave background or CMB, gave astrophysicists tangible proof of the big bang that kick-started the universe. Study of the CMB led to Nobel Prizes, including one to Dr. John Mather and Dr. George Smoot.

Now Thomas Essinger-Hileman is leading a team developing new microwave sensors that could power more precise images to help find patterns in the polarization of the CMB.

Essinger-Hileman said those patterns could confirm one of the key theories about what happened right after the big bang: a few short moments of rapid, exponential expansion, called cosmic inflation, that is beyond our current understanding.

"We really need to go out and look for a firm signature," he said. "If inflation did occur, the polarization of the cosmic microwave background would show gravitational waves that would imprint very specific swirl patterns in the polarization of the background radiation."

Detecting those patterns could provide a missing piece of the current standard model of particle physics, Essinger-Hileman said, "at energy scales 13 orders of magnitude above what particle accelerators can produce."

Cold Light

The nature of microwave light presents several hurdles to measuring it in the level of detail they seek. Microwaves have longer wavelengths than visible light, requiring larger individual pixel detectors. In addition, the CMB is incredibly cold – about 2.7 Kelvin, or degrees Celsius above absolute zero. The observed microwave background mostly fluctuates within a 50 millikelvin – or 0.00005 degrees Celsius – range, and the swirl pattern in the polarization is at nanokelvin (a billionth of a degree Celsius) levels.

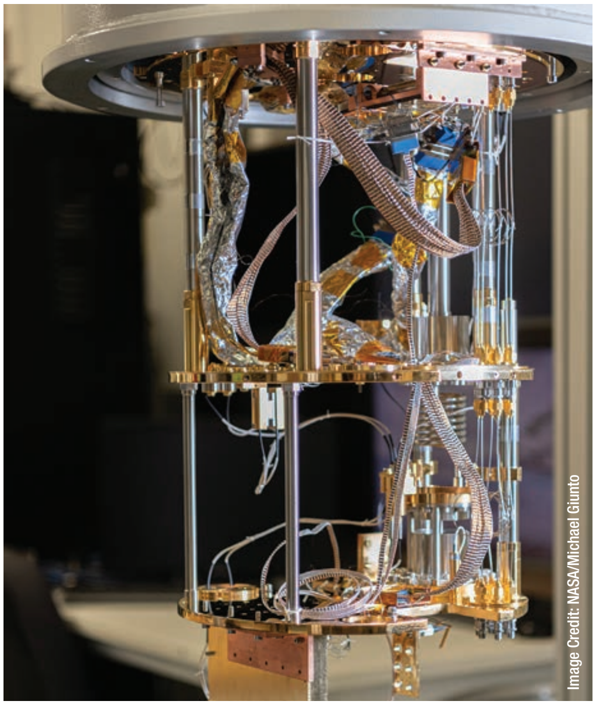
"At these wavelengths," Essinger-Hileman said, "you need extremely sensitive detectors, which makes them sensitive to temperature fluctuations within the instrument itself. Their resistance changes really rapidly with temperature."

Along with post-doctoral researcher Sumit Dahal, they tested the detectors in a cryogenic system this spring, using Center Innovation Funds. The sensors were cooled to 100 millikelvin, or 0.1 degree Celsius above absolute zero.

The larger pixels and ultracold temperatures required by these detectors, measuring up to 2 centimeters on a side, present physical challenges to developing a large sensor array. Cell phone cam-eras have millions of pixels to detect visible light. To capture the faint swirl patterns in polarization at microwave wavelengths, which are about 2,000 times longer, their team is working hard to develop a camera with even thousands of pixels.

Standing on Shoulders of Giants

The COsmic Background Explorer (COBE), which gave Mather and colleagues the first image of the cosmic microwave background, had a limited number of detectors. Since then, the Wilkinson



A microwave spectrum detector suspends from a cooling mechanism for cryogenic testing at less than one degree Kelvin above absolute zero.

Microwave Anisotropy Probe (WMAP) and the ESA's Planck spacecraft have increased the number of detectors and added capability to detect the polarization, or orientation, of microwave light.

Essinger-Hileman and team are building on work begun at Goddard by physicist Ed Wollack as well as David Chuss, who is now at Villanova University in Pennsylvania. The team also includes physicist Karwan Rostem, who contributed to chip development, and engineers Kevin Denis and Kongpop U-Yen.

For ground-testing their technology, they provided detectors and support for Johns Hopkins University's Cosmology Large Angular Scale Surveyor, or CLASS, telescope in Chile's Atacama Desert. CLASS is led by JHU physicists Charles Bennett and Tobias Marriage.

While the ground-based observatory will have to contend with weather, ground-based microwave interference and other limitations not experienced in space, Essinger-Hileman said "the experiments there can still do scientifically interesting work, however, the ultimate goal is a space mission. That's where you would get the best all-sky coverage without interference."

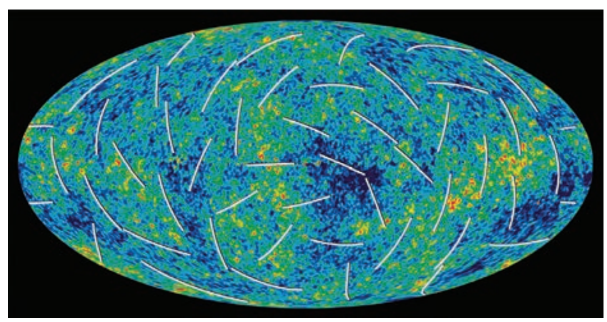
Still a decade off, they hope to prove their technology in time for the proposed Probe of Inflation and Cosmic Origins (PICO) or other future CMB satellite missions.

Future Payoffs

The goal of these missions is nothing short of peering back to the first moments after the big bang, shedding light on the nature of dark matter and dark energy, searching for new fundamental particles, and understanding star formation over cosmic time.

Detecting gravitational waves in the background radiation, Essinger-Hileman said, would provide the first evidence of a quantum gravitational process. Current theories of general relativity, which describes gravity, and quantum theory, which describes everything else, are separate domains which don't work very well together.

"Observing direct evidence that gravity in some form is a quantum field could point physicists toward a theory that could unite these theories," he said. ❖



The Wilkinson Microwave Anistotropy Probe's (WMAP) three-year picture of the infant universe shows "warmer" (red) and "cooler" (blue) spots. The white bars show the "polarization" direction of the oldest light. Higher resolution imaging of this polarization could provide clues about the nature of the universe and what happened its first trillionths of a second.

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