National Aeronautics and Space Administration

# Cutting edge
Goddard's Emerging Technologies

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## Where Do We Go from Here?

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SPECIAL REPORT
2020 Decadal Survey for Astrophysics

# Where Do We Go from Here?

*NASA Teams Study Four Possible Next-Generation Astrophysics Missions*

What does NASA's future look like? Will the next-generation telescope investigate the first black holes in the distant universe or will it look for life on an Earth-like planet light-years away? As in past decades, the agency won't make that decision in a vacuum or without understanding the technical obstacles, which are formidable.

Already, teams of experts from across the agency, academia, and industry are studying four potential flagship missions that the science community has vetted as worthy pursuits under the 2020 Decadal Survey for Astrophysics. All four teams recently submitted interim reports. Next year, they are expected to finish final reports that the National Research Council then will use to inform its recommendations to NASA in a couple years.

"This is game time for astrophysics," said Susan Neff, chief scientist of NASA's Cosmic Origins Program. "We want to build all these concepts, but we don't have the budget to do all four at the same time. The point of these decadal studies is to give members of the astrophysics community the best possible information as they decide which science to do first."

Goddard is playing a vital role in the effort. Center scientists and engineers are participating in all four studies and leading two: the Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) and the Origins Space Telescope (OST). Meanwhile, NASA's Jet Propulsion Laboratory (JPL) and the Marshall Space Flight Center are, respectively, leading the Habitable Exoplanet Imaging Mission (HabEx) and the X-ray Surveyor, known as Lynx (see sidebar, page 3).

*Continued on page 4*

## in this issue:

Spring 2018




## About the Cover

Goddard's Aki Roberge (left) and Dave Leisawitz are study scientists for two Goddard-led investigations looking into potential next-generation observatories to succeed the James Webb Space Telescope. Their findings — as well as those of two other NASA teams — will inform the National Research Council's 2020 Decadal Survey for Astrophysics. Due next year, the studies outline the observatories' science goals and technology obstacles, which researchers say are formidable.

Photo Credit: Bill Hrybyk/NASA

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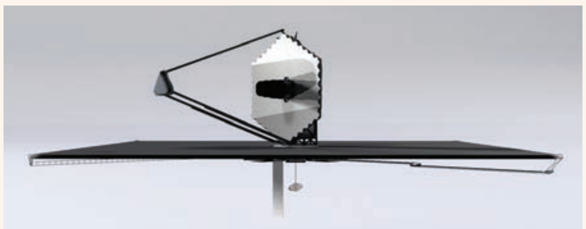
SPECIAL REPORT
2020 Decadal Survey for Astrophysics

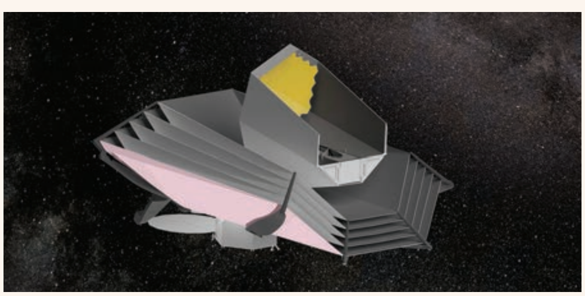
# 2020 Decadal Survey Missions: At a Glance

Any telescope that reaches the launch pad in the 2030s will likely look much different than the concepts four teams are currently studying to inform the 2020 Decadal Survey for Astrophysics, but the studies do offer a roadmap. Here's a brief overview of each:



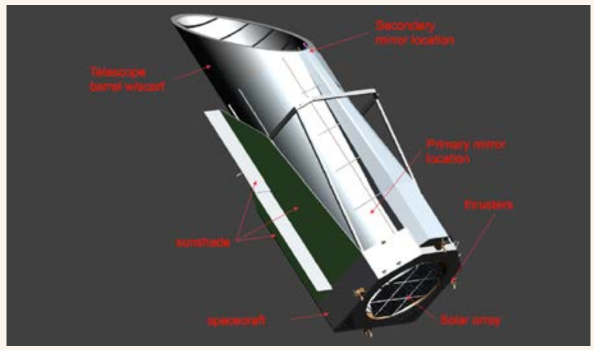
## Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR)

LUVOIR, now being studied by a Goddard team, is conceived as a great observatory in the tradition of the Hubble Space Telescope. LUVOIR will tell the story of life by searching for signs of life on exoplanets and exploring the cosmic origins of life. Its specific capabilities will span exoplanetary science, general astrophysics, and solar system science. As its name implies, LUVOIR would cover wavelengths from the far ultraviolet to the near infrared and its primary mirror could be up to six times larger than Hubble's.



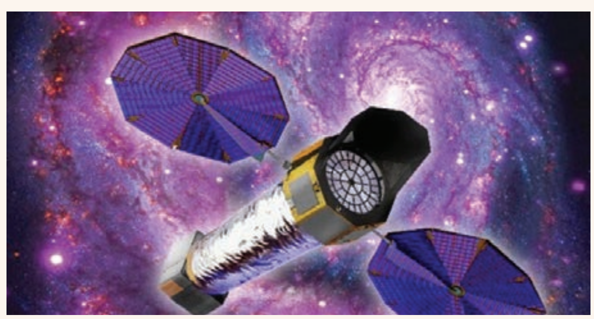
## Origins Space Telescope (OST)

OST, another concept that a Goddard team is investigating, would be extraordinarily sensitive in the mid- to far-infrared wavelengths. Through imaging and spectroscopy, it would probe the early universe, trace the path of water through star and planet formation, and search for signs of life in the atmospheres of exoplanets. Considered a follow-on to the Spitzer Space Telescope and the Herschel Space Observatory, OST would offer 10,000 times more sensitivity than any preceding far-infrared telescope.




## Habitable Exoplanet Imaging Mission (HabEx)

The Jet Propulsion Laboratory is leading the HabEx study. This observatory would directly image planetary systems around Sun-like stars. By measuring the spectra of these planets, HabEx would search for signatures of habitability, including water, oxygen, or ozone. It would also study the early universe and the lifecycle of massive stars. Like LUVOIR, HabEx would be sensitive to ultraviolet, optical, and near-infrared wavelengths.



## Lynx

Lynx, which the Marshall Space Flight Center is studying, would investigate the universe in X-rays. It is expected to offer a two orders-of-magnitude leap in sensitivity over Chandra and the European Space Agency's Advanced Telescope for High-Energy Astrophysics, or Athena, which is due to launch in 2028. It would detect X-rays from black holes at the centers of the first galaxies and from young stars and their planetary systems.

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## SPECIAL REPORT
### 2020 Decadal Survey for Astrophysics

Regardless of which mission NASA ultimately selects or the technologies it flies, the agency and individual centers have begun investing in advanced tools needed to pursue these bold, breakthrough concepts in the future, said Thai Pham, the technology development manager for NASA's Astrophysics Program Office. "I'm not saying it will be easy. It won't be," he continued. "These are ambitious missions, with significant technical challenges, many of which overlap and apply to all. The good news is that the groundwork is being laid now."

## Unprecedented Picometer-Level Stability

LUVOIR provides a case in point.

One concept of the observatory envisions a supersized, segmented primary mirror about 49 feet in diameter. With this behemoth, LUVOIR could help answer how life began, what conditions are vital for the formation of stars and galaxies, and perhaps most compellingly, is Earth rare in the cosmos?

"LUVOIR will search for signs of life, but it doesn't stop there. It will tell us how life got there and how rare life is in the cosmos," said Shawn Domagal-Goldman, deputy study scientist. "This mission is ambitious," agreed study scientist Aki Roberge, "but finding out if there is life outside the solar system is the prize. All the technology tall poles are driven by this goal."

To directly image Earth-sized planets and assess their atmospheres, LUVOIR would have to acquire light from a relatively tiny object at least 10 billion times fainter than the star it encircles. This would be like discerning an object no wider than a

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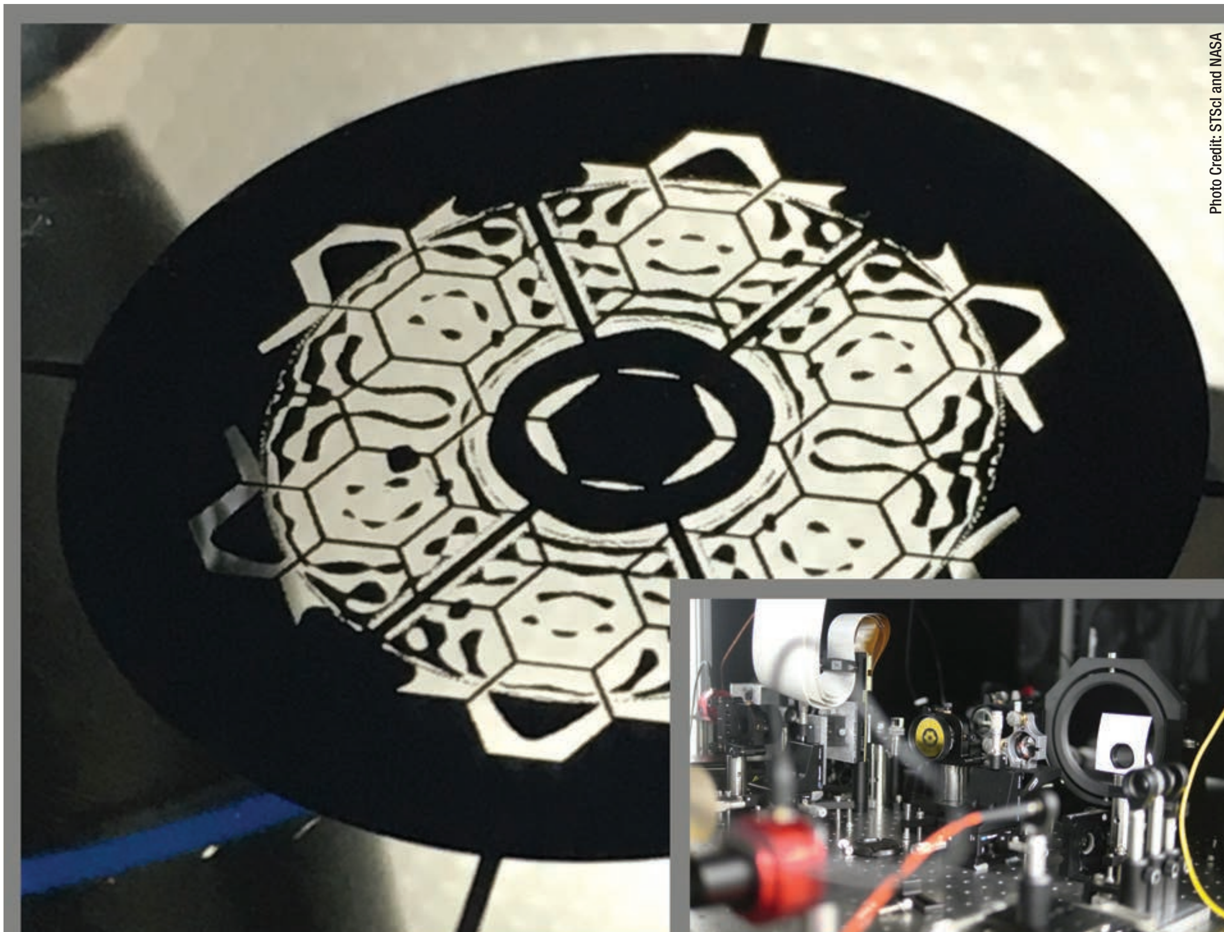
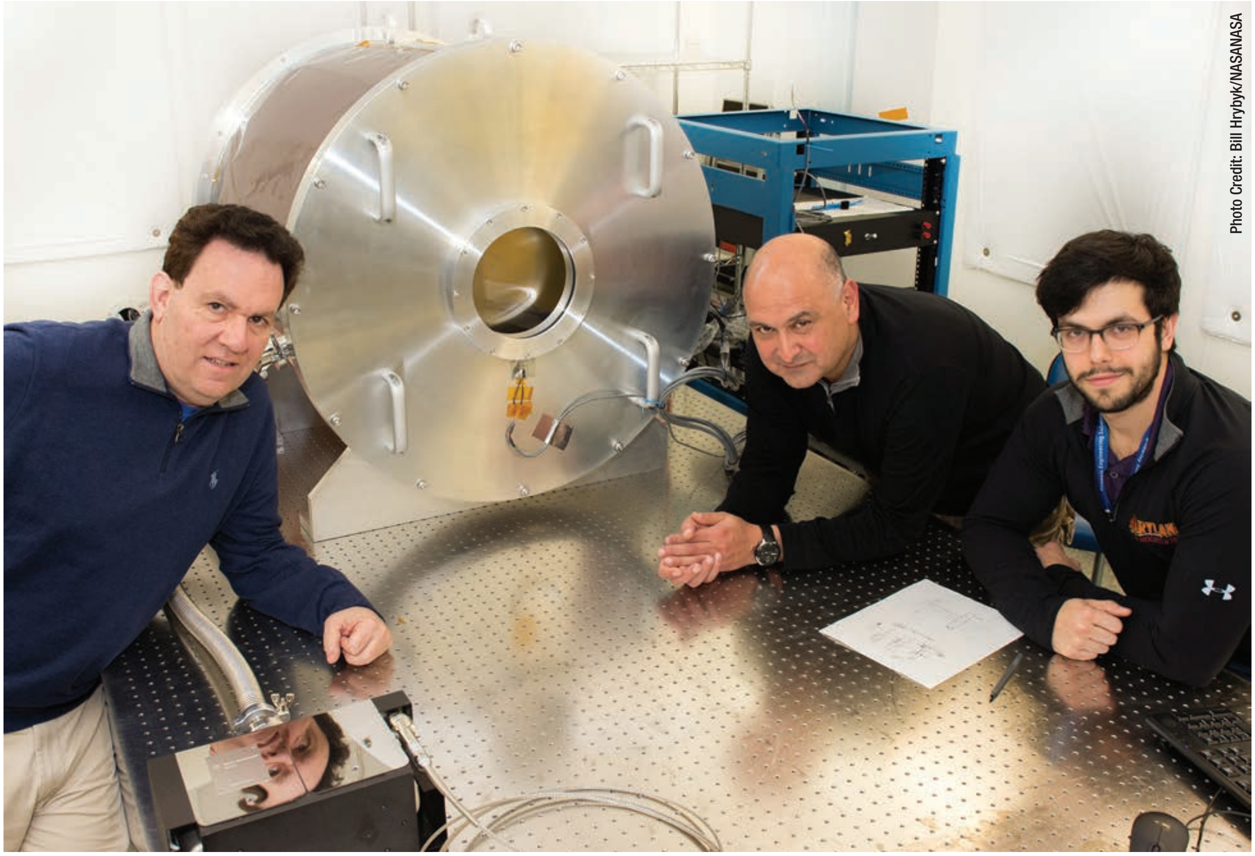


Photo Credit: STScI and NASA

*The Space Telescope Science Institute has created a testbed for evaluating different coronagraphic approaches primarily for a mission called LUVOIR. Here is one possible solution: a mask coated with carbon nanotubes fashioned to modify the pattern of diffracted light. The inset photo is a close-up view of the testbed and the gold-colored carbon-nanotube mask.*




*(From left to right): Technologists Lee Feinberg, Babak Saif, and Eli Griff-McMahon have created an ultra-stable thermal-vacuum system that they are using to make picometer-level measurements necessary for LUVOIR.*

human hair from a distance of two football fields, Roberge said.

To do this, LUVOIR's optics and associated hardware must be ultra-stable; that is, these components can't move or distort more than 12 picometers — a measurement smaller than the size of a hydrogen atom. Not only would the observatory have to maintain these exacting standards while making a measurement, so would its mirror segments.

Like the 21-foot primary mirror on the James Webb Space Telescope, LUVOIR's mirror would be made up of adjustable segments that would unfold after launch. Because capturing light from a faint and distant source would require a precisely focused wavefront, actuators or motors attached to the back of each mirror would then actively adjust and align the segments to achieve a perfect focus.

"Physical stability, plus active control on the primary mirror and an internal coronagraph (a device for blocking starlight) will result in picometer accuracy," Roberge said. "It's all about control."

Already a Goddard team has begun developing laboratory tools that can dynamically detect picometer-sized distortions that occur when materials used to build telescopes shrink or expand due to wildly fluctuating temperatures or when exposed to fierce launch forces. Should NASA select LUVOIR as its next flagship mission, NASA could use this tool to assure that the agency builds an observatory to these benchmarks (CuttingEdge, Winter 2018, Page 8).

## Suppressing Starlight: A Shared Technical Challenge

HabEx, though physically smaller than LUVOIR, would also directly image planetary systems and analyze the composition of the planets' atmospheres. Like LUVOIR,

*Continued on page 6*



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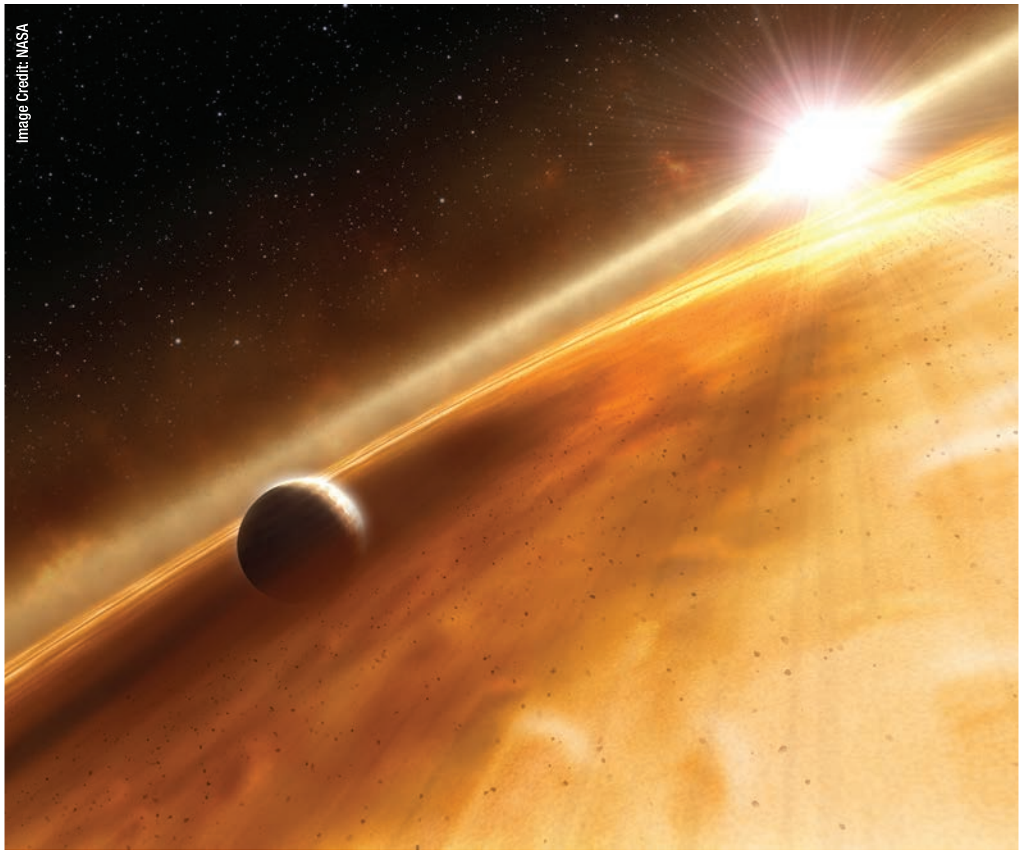
it, too, must fly technologies to block the parent star's bright light and create a dark zone revealing the presence of an Earth-sized planet.

"To directly image a planet orbiting a nearby star, we must overcome a tremendous barrier in dynamic range: the overwhelming brightness of the star against the dim reflection of starlight off the planet, with only a tiny angle separating the two," said Neil Zimmerman, a NASA expert in the field of coronagraphy. "There is no off-the-shelf solution to this problem because it is so unlike any other challenge in observational astronomy."




*Like LUVOIR, HabEx would search for and analyze the atmospheres of Earth-like planets orbiting stars light-years from Earth. This artist's rendering shows a potential target.*

To overcome the challenge — likened to trying to photograph a firefly circling a streetlight from thousands of miles away — researchers are studying different approaches for suppressing starlight, including external petal-shaped star shades that block light before it enters the telescope and internal coronagraphs that employ masks and other components to prevent starlight from reaching the detectors. The HabEx team is investigating both techniques.

But a big hurdle remains: even with multiple coronagraphic masks, starlight will still get through, said Rémi Soummer, a scientist at the Space Telescope Science Institute in Baltimore, Maryland. Starlight will diffract off the edges of a coronagraph's optical components, making it difficult to completely block the light to see a small planet orbiting the star. One possible solution is to apply carbon nanotubes onto the coronagraphic masks that modify the pattern of diffracted light (see related story, page 18).

Soummer, who created a state-of-the-art testbed for evaluating different coronagraphic approaches primarily for LUVOIR, is collaborating with former Goddard optical engineer John Hagopian to test the effectiveness of Hagopian's carbon-nanotube technology for this application. This super-black coating consists of multi-walled nanotubes 10,000 times thinner than a strand of human hair. "When light penetrates the nanotube forest with minimal reflection, the light's electric field excites the electrons, turning light to heat and effectively absorbing it," explained Hagopian, now a Goddard contractor.

Test results so far are promising, Soummer said. But the verdict is still out. While Hagopian works to improve his technology's ability to absorb nearly all light, Soummer plans to test coronagraph masks using another light-suppression technology called silicon grass. Developed by JPL researchers, silicon grass consists of a forest of tiny needles etched into the surface of a thin silicon wafer. "My job is to

*Continued on page 7*

compare the performance of the different techniques," Soummer said.

## "Detectors, Detectors, Detectors"

Although large arrays of detectors measuring in the millions of pixels are a must for LUVOIR, HabEx, and Lynx, they are particularly important for OST, a far-infrared observatory designed to observe the farthest reaches of the universe.

"When people ask about technology gaps in developing the Origins Space Telescope, I tell them the top three challenges are detectors, detectors, detectors," said Dave Leisawitz, a Goddard scientist and OST study scientist. "It's all about the detectors."

NASA researchers are currently advancing different types of superconducting detectors for next-generation telescopes, but OST could benefit more from either of two emerging types: Transition Edge Sensors (TESs) or Kinetic Inductance Detectors (KIDs).

TES detectors have reached a high degree of technological maturity and are now used in HAWC+, an instrument on NASA's Stratospheric Observatory for Infrared Astronomy, commonly known as SOFIA. "While relatively early in its technology-readiness, KIDs are quickly maturing, and also may find uses in future astronomical instruments," said Johannes Staguhn, a detector expert at Goddard and deputy study scientist and instrument scientist for OST.

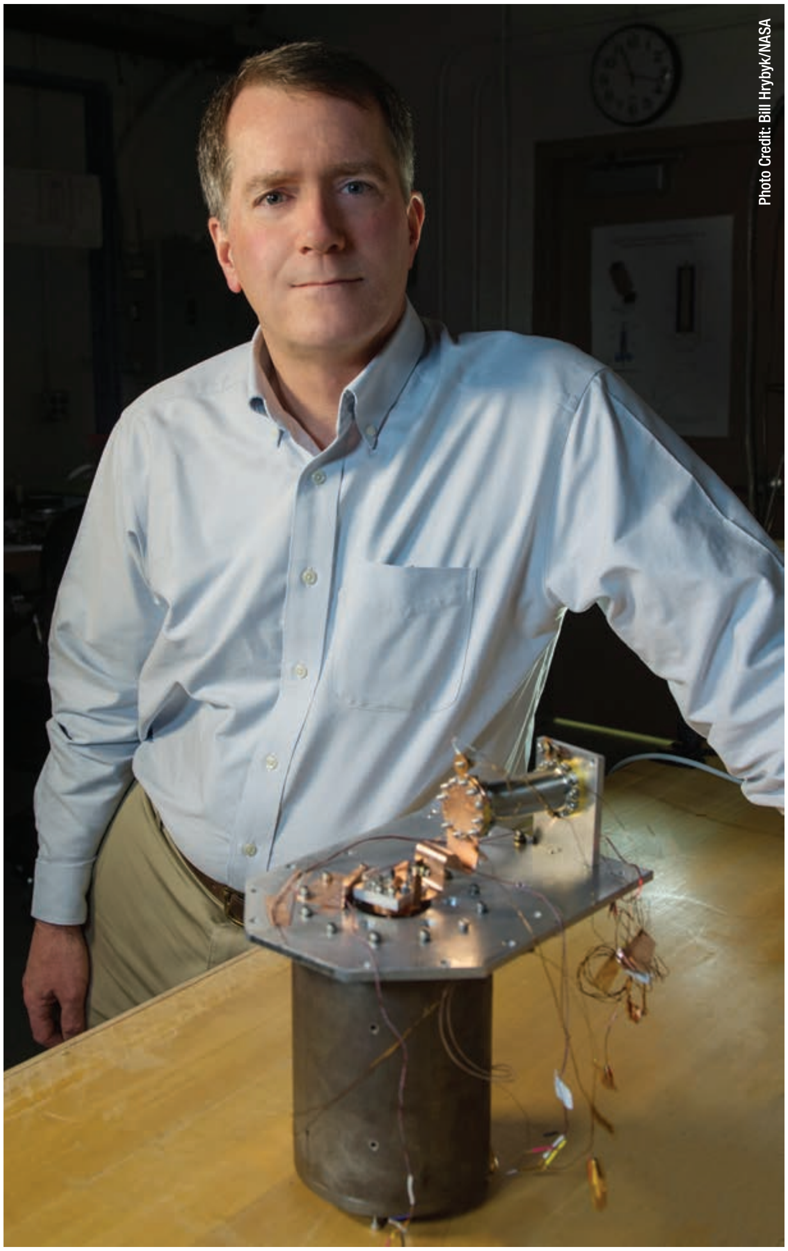


Photo Credit: Bill Hrybyk/NASA

*Goddard cryogenic engineer Jim Tuttle is advancing a cooling technology called the continuous adiabatic demagnetization refrigerator.*

However, neither detector technology can fulfill its promise unless the observatory is actively cooled to a frosty 4 kelvin, or -452.47 degrees Fahrenheit. That's because the light it's collecting — light that first began its journey across the universe literally billions of years ago — reaches Earth as heat. If the observatory and its instruments generate too much heat, it will overwhelm the signal the telescope wants to collect and measure.

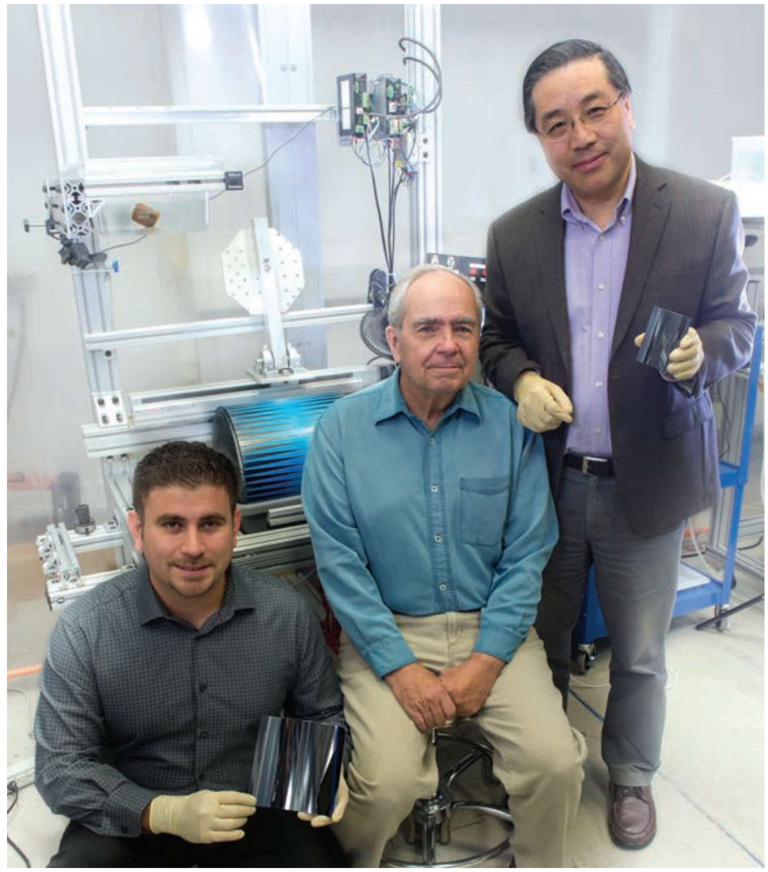
As a result, OST's segmented primary mirror — now projected to span nearly 30 feet in diameter — would have to be cooled to about 4 K, representing the first time NASA will have flown an actively cooled telescope. According to Leisawitz, the OST team would like to achieve this by flying layers of sunshields that would envelope the mirror and ra-

*Continued on page 8*

diate heat away from it. Four cryocoolers or heat sinks then would mechanically absorb the residual heat to maintain the mirror's 4 K target temperature.

OST's instrument detectors must be cooled as well — to 0.05 K, or one twentieth of a degree above absolute zero. This is 80 times colder than the observatory itself, and the study team believes it can accomplish this technical feat with a multi-stage Continuous Adiabatic Demagnetization Refrigerator (CADR).

The technology, developed by Goddard cryogenic engineers, has flown on past X-ray missions. It cools to this very low temperature by varying the magnetic fields inside rods of specialized materials and ultimately conducting heat away to a 4 K cryocooler. "The CADR has no moving parts, produces no vibrations, and works independently of gravity, making it very suitable for space missions," said Goddard cryogenic engineer Jim Tuttle.



*Goddard scientist Will Zhang (right) is developing a new X-ray mirror made of silicon, which he believes will benefit the Lynx mission. Both he and Raul Riveros (left), who has helped advance the process, are holding curved mirrors they manufactured. Goddard technologist Vince Bly (middle) began experimenting with the material as a potential mirror-making material several years ago.*

## Mirrors and Cool Detectors to Reveal the Hidden Universe

Cooling technologies and higher-performing detectors also present challenges for Lynx. Named after the sharp-sighted feline, the proposed observatory is the only of the four to examine the universe in X-rays. One of its principal jobs would be to detect this more energetic form of light coming from supermassive black holes at the center of the very first galaxies.

"Supermassive black holes have been observed to exist much earlier in the universe than our current theories predict," said Rob Petre, a Lynx study member at Goddard. "We don't understand how such massive objects formed so soon after the time when the first stars could have formed. We need an X-ray telescope to see the very first supermassive black holes, in order to provide the input for theories about how they might have formed."

To unravel the mystery, the Lynx study team is considering flying an X-ray microcalorimeter imaging spectrometer, among other instruments. With microcalorimetry, X-ray photons strike the detector's absorbers and their energy is converted to heat, which a thermometer then measures. The heat is directly proportional to the X-ray's energy, which can reveal much about the target's physical properties. Because microcalorimeters essentially are thermometers, they must be cooled to cryogenic temperatures to detect these fleeting, hard-to-capture X-rays.

NASA has made strides in these areas, Petre said. A Goddard team provided the cooling technology, a two-stage ADR, and a 36-pixel microcalorimeter array for the Japanese Suzaku and Astro-H missions. For Lynx, however, these technologies must become larger and more capable.

Currently, Goddard scientists Simon Bandler and Caroline Kilbourne are scaling up the size of the mi-

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crocalorimeter array and, in fact, are developing a 4,000-pixel microcalorimeter array for the European Space Agency's Advanced Telescope for High-Energy Astrophysics, or Athena, mission. Athena is expected to launch in the late 2020s. Their goal is to ultimately create an array containing 100,000 pixels. Meanwhile, Goddard cryogenic experts, led by Tuttle, are adding stages to the refrigerator. The same multi-stage cooling system baselined for Lynx also could be used on OST, Tuttle said.

Lynx also would require a lightweight optic offering a significantly larger collection area and dramatically improved resolution. Unlike other mirrors that collect less energetic light, X-ray optics must be curved and nested inside a canister so that incoming photons graze the mirrors' surface and deflect into the observatory's instruments. The greater the number of mirrors, the higher the resolution.

One possible approach is using a relatively inexpensive, easily reproducible optic made of single-crystal silicon, a hard, brittle, non-metallic element used to make computer chips. Now being developed by NASA optics expert Will Zhang, the material has proven effective at gathering X-rays (CuttingEdge, Winter 2017, Page 2), Petre said. Because these mirrors are thin and lightweight, Lynx could carry thousands of individual mirror segments to improve its light-gathering power.

Although two other competing technologies exist, Zhang is confident Lynx would profit from his work. "The quality of the mirrors we are making today is several times better than a year ago. We are meeting or close to meeting Lynx requirements, but a year or so from now, we definitely will be meeting them." ❖

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# Emerging Microgap Cooling to be Tested Aboard Reusable Launch Vehicle

An emerging technology for removing excessive, potentially damaging heat from small, tightly packed instrument electronics and other spaceflight gear will be demonstrated for the first time during a suborbital flight aboard a reusable launch vehicle this fall.

Goddard thermal engineer Franklin Robinson is scheduled to fly his experiment aboard the fully reusable Blue Origin New Shephard launch vehicle to prove that the microgap-cooling technology is immune from the effects of zero gravity (CuttingEdge, Fall 2015, Page 17).

The demonstration, funded by NASA's Space Technology Mission Directorate, is an important step in validating the system, which engineers believe could be ideal for cooling tightly packed, high-power integrated circuits, power electronics, laser heads, or other devices. The smaller the space between these electronics, the harder it is to remove the heat. Because these devices are vulnerable to overheating — just like any electronic device on Earth — the cooling technology must operate under all conditions, including the microgravity environment found in space.

> *"While theory predicts that the lack of gravity would have a negligible impact on the performance of microgap coolers, this needs to be demonstrated in a space-like environment. Otherwise, potential users are unlikely to commit to the technology."*
>
> ***– Ted Swanson, Sr. Technologist for Strategic Integration***

"Frank (Robinson) is demonstrating the fundamental concept and we need the flight validation to gain confidence," said Senior Technologist for Strategic Integration Ted Swanson. "While theory predicts that the lack of gravity would have a negligible impact on the performance of microgap coolers, this

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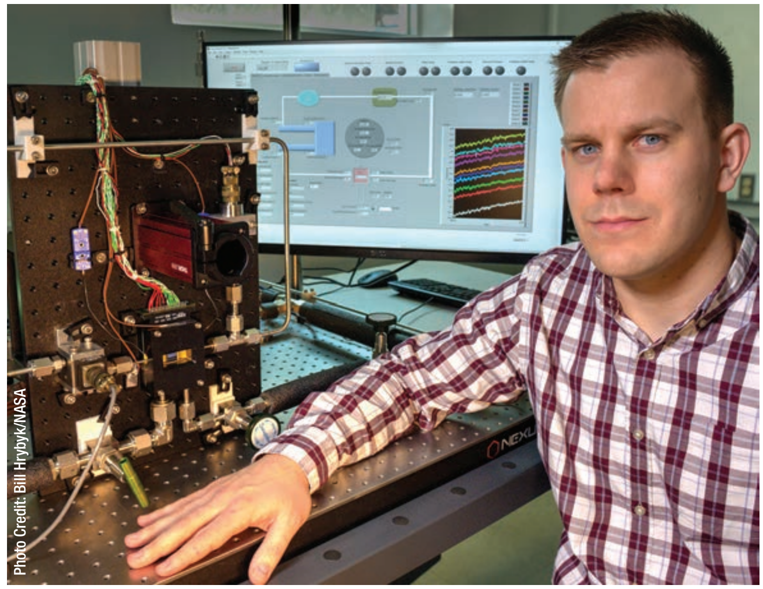
needs to be demonstrated in a space-like environment. Otherwise, potential users are unlikely to commit to the technology."




Goddard technologist Frank Robinson is shown here with the microgap-cooling technology he will test on the fully reusable Blue Origin New Shephard launch vehicle this summer.

## Microchannel Conduits

With microgap cooling, heat generated by electronics and other devices is removed by flowing a coolant through embedded, rectangular-shaped channels within or between heat-generating devices. Robinson's flight experiment also features "flow boiling," where, as its name implies, the coolant boils as it flows through the tiny gaps. According to Robinson, the technique offers a higher rate of heat transfer, which keeps devices cooler, and, therefore, less likely to fail due to overheating.

To remove heat in more traditional electronic devices, designers create a "floor plan." They keep the heat-generating circuits and other hardware as far apart as possible. The heat travels into the printed circuit board, where it is directed to a clamp in the sidewall of the electronics box, eventually making its way to a spacecraft-mounted radiator.

Traditional approaches, however, would not work well for emerging 3-D integrated circuitry — a highly promising technology that could satisfy users' thirst for more computing power.

With 3-D circuitry, computer chips literally are stacked atop one another and not spread over a circuit board, saving space in electronic devices and instruments. Interconnects link each level to its adjacent neighbors, much like how elevators connect one floor to the next in a skyscraper. With shorter wiring linking the chips, data moves both horizontally and vertically, improving bandwidth, computational speed, and performance, all while consumming less power.

Because not all the chips are in contact with the printed circuit board, traditional cooling techniques wouldn't work well with 3-D circuitry, Robinson said, adding he began his research with NASA support to assure that the agency could take advantage of 3-D circuitry when it became available. "However, we can remove the heat by flowing a coolant through these tiny embedded channels."

## Testing Effectiveness in Microgravity

Although Robinson has tested his cooling technology at various orientations in a laboratory, the question is whether it would be equally effective in space. "What we need to determine is how small the channels must be to achieve gravity independence. Right now, we don't have a perfect understanding," he said.

Should the microgap technology succeed during the demonstration, the next step would be to find an actual application and demonstrate it in space, Swanson said.

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The Blue Origin New Shephard launch vehicle (pictured here) is flying an experiment designed to prove that the microgap-cooling technology is immune from the effects of zero gravity, and therefore, potentially useful for removing heat from tightly packed electronics on spaceflight instruments.

# "Third Time's a Charm"

*Heliophysics Wins Pathfinding CubeSat Mission; New Dellingr Satellite Bus Baselined*

A new CubeSat mission — GTOSat — will do more than monitor the environmentally forbidding radiation belts that encircle Earth.

This mission of firsts will serve as a pathfinder for new radiation-tolerant technologies that could help scientists realize a long-sought dream: deploying a constellation of small satellites beyond low-Earth orbit to gather simultaneous, multi-point measurements of Earth's ever-changing magnetosphere, which protects the planet from the constant assault of charged particles streaming off the Sun.

Furthermore, it will be the first CubeSat to operate in geostationary transfer orbit, or GTO — from which it derives its name. And last it's the first to use the latest, more robust version of the Goddard-developed Dellingr spacecraft bus — the Dellingr-X.

## NASA HTIDeS Awards GTOSat and Others

"Third time's a charm," said Goddard scientist Larry Kepko, who had tried before to secure funding under NASA's Heliophysics Technology and Instrument Development for Science (HTIDeS) program to build and launch the mission. In addition to GTOSat, the HTIDeS program awarded funding to four other CubeSat missions and 13 sounding-rocket and balloon missions — six involving Goddard personnel and instruments. Two Goddard scientists also received instrument-development funds to advance technologies for imaging the solar corona and flares.

Expected to launch in early 2021, the $4.5-million GTOSat will gather measurements from a highly elliptical Earth orbit that is a standard interim orbit for communications satellites operating in geostationary orbit about 22,000 miles from Earth. From that location, GTOSat will use its two onboard instruments to measure high-energy particles that likely originate from solar wind and cosmic rays.

These particles gyrate, bounce, and drift through two concentric, donut-shaped rings called the Van Allen belts, sometimes shooting down to Earth's atmosphere or escaping into space. Named for James Van Allen, their discoverer, these radiation belts are located in the inner region of Earth's magnetosphere. There they swell and shrink over time as part of a much larger space-weather system that can disrupt satellites and GPS communications, cause power-grid failures, and even threaten the health and safety of astronauts working in low-Earth orbit.

"These energetic particles can damage spacecraft and pose significant risks to astronaut health," said GTOSat Principal Investigator Lauren Blum, who submitted the winning proposal. "This region of space isn't just scientifically interesting. It directly affects us here on Earth."

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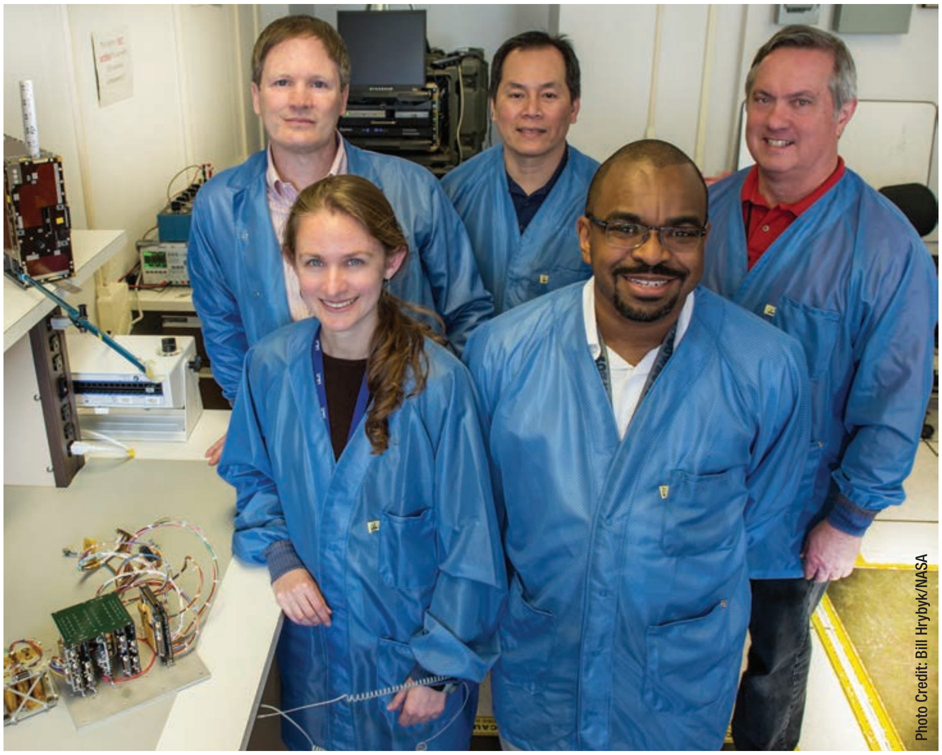
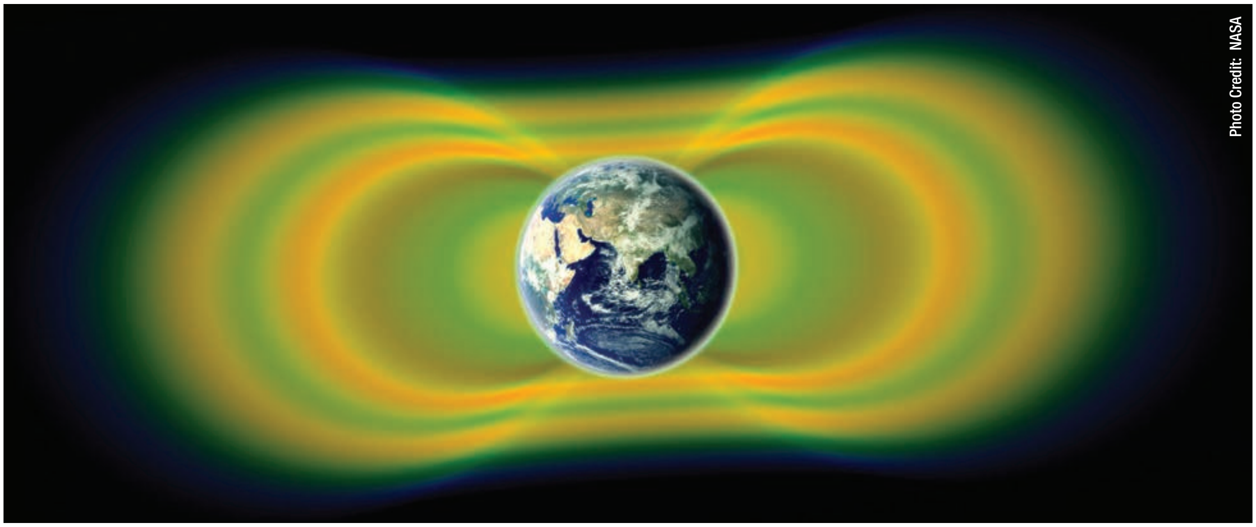


Photo Credit: Bill Hrybyk/NASA

*Scientist Lauren Blum and her team, who are shown with more robust command and data handling and electrical power systems, have won a new CubeSat mission that will study the Van Allen radiation belts. From left to right (back): Larry Kepko, Hanson Nguyen, Chuck Clagett; (front): Blum and James Fraction.*




*Studying the Van Allen radiation belts is the scientific goal of the recently awarded GTOSat, which will use a more capable CubeSat bus, the Dellingr-X.*

Currently, NASA's Van Allen Probes, the second mission of NASA's Living With a Star program, are providing unprecedented insight into the physical dynamics of the radiation belts and are providing scientists the data they need to make predictions of changes in this critical region of space.

However, the two probes, which launched in 2012, are running out of fuel and are expected to retire in a couple years. GTOSat will provide data after their mission ends, Blum said.

## Dellingr-X Offers Solution

To continue gathering measurements of the Van Allen belts, however, the GTOSat team needed to assure that the spacecraft bus and its instruments could withstand the hostile environment that larger, more traditional spacecraft — like the probes — are built to tolerate. A successful CubeSat mission demanded that its hardware and software were hardened against the onslaught of charged particles, which can destroy electronics and ultimately end missions, Blum said, adding that to date most CubeSat missions operate far below the altitude of the Van Allen belts.

The Dellingr-X spacecraft offered the perfect solution.

A follow-on to the original shoebox-sized Dellingr that engineers specifically designed to be less expensive, more reliable, and capable of executing NASA-class science (*CuttingEdge*, Summer 2017, Page 2), Dellingr-X adds a new level of capability.

Dellingr-X's all-important command and data handling and electrical power systems will be radiation tolerant; in other words, they will be able to withstand high-energy particle hits that sometimes cause electronic systems to latch-up and draw too much current.

Both technologies were developed under the Goddard Modular SmallSat Architecture (GMSA) program, which the center initiated to create overarching system designs and technologies to dramatically reduce mission risks without significantly increasing the cost of smaller platforms (*CuttingEdge*, Winter 2017, Page 7).

## Future Missions to Benefit

Enabling GTOSat isn't the only benefit of these new GMSA technologies, Kepko said.

NASA is studying a couple constellation-type missions that might employ as many as 36 SmallSats — spacecraft larger than CubeSats but smaller and less expensive than more traditional satellites — in multiple locations within the magnetosphere that encompasses the Van Allen belts. Dellingr spacecraft wouldn't be appropriate for these types of missions due to their small size, but a GMSA-based SmallSat weighing between 110-220 pounds would be, he said.

As a pathfinding mission, the relatively inexpensive GTOSat will demonstrate these new GMSA technologies and give them flight heritage, he added. "This paves the way and opens the door to eventually flying multiple satellites in a SmallSat constellation beyond low-Earth orbit — something I've waited my entire career to happen but hasn't because it's prohibitively expensive to build and fly multiple, more traditional spacecraft." ❖

### CONTACTS

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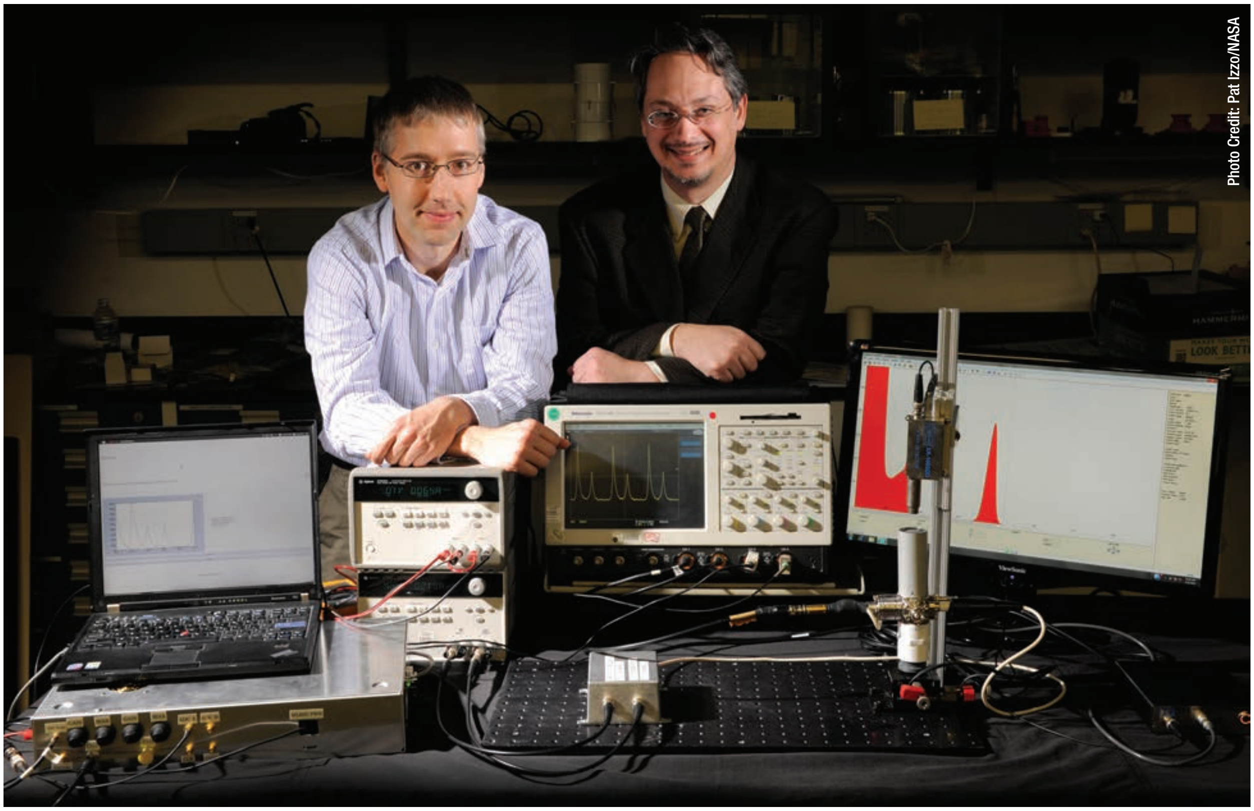
# XNAV Considered for Possible CubeSat Mission; NASA Studies as Technique for Human Exploration




*Engineers Luke Winternitz (left), Jason Mitchell (right), and their team developed a unique tabletop device — aptly described as a "pulsar on a table" — to simulate rapid-fire X-ray pulsations needed to test algorithms and other advanced technologies for X-ray navigation. The team recently delivered the special testbed to the Orion development team at the Johnson Space Center.*

Now that NASA has proven the viability of autonomous X-ray navigation in space, a team led by the Smithsonian Astrophysical Observatory plans to include the technology on a proposed CubeSat mission to the Moon, and NASA engineers are now studying the possibly of adding the capabilities to future human exploration spacecraft.

The pursuit of this emerging capability to pilot spacecraft to the far reaches of the solar system comes just months after Goddard scientist Keith Gendreau and his team successfully demonstrated the technique — commonly known as XNAV — with an experiment called Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) (*CuttingEdge*, Winter 2018, Page 2).

The demonstration, which took place late last year, proved that millisecond pulsars could be used to accurately determine the location of an object moving at thousands of miles per hour in space. These pulsations are highly predictable, much like the atomic clocks used to provide timing data on the ubiquitous GPS system.

During that demonstration, SEXTANT took advantage of the 52 X-ray telescopes and silicon drift detectors on NASA's Neutron-star Interior Composition Explorer (NICER), to detect X-rays emanating from four millisecond-pulsar targets. The pulsars' timing data were fed into onboard algorithms to autonomously stitch together a navigational solution revealing the location of NICER in orbit around Earth.

The team is expected to carry out another XNAV demonstration later this spring to see if it can improve on the technology's already impressive accuracy, said SEXTANT Project Manager Jason Mitchell.

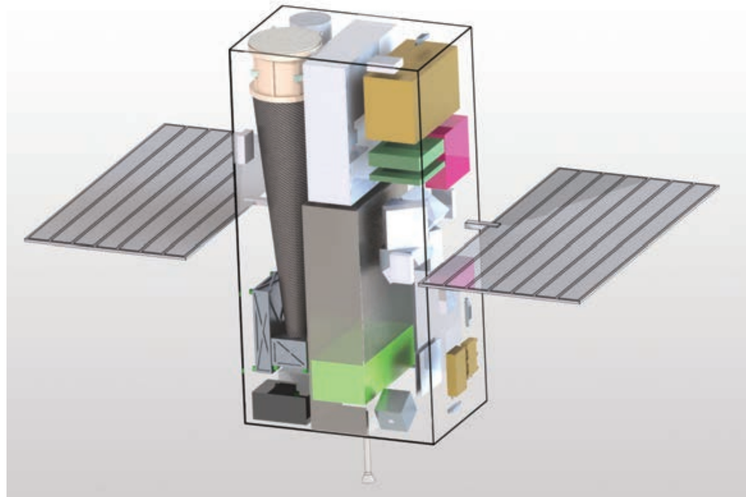
## Orion Navigation Testbed

In another development that could broaden XNAV's use, the SEXTANT team recently delivered a special

*Continued on page 14*

testbed to the Orion development team at the Johnson Space Center. Mitchell, Luke Winternitz, Munther Hassouneh, and Sam Price developed the unique tabletop device — aptly described as a "pulsar on a table" — to simulate rapid-fire X-ray pulsations needed to test algorithms and other advanced technologies for the XNAV demonstration.

The Orion spacecraft development team will integrate the technology into its navigation testbed to evaluate the viability of XNAV as a potential technique to support future navigation of the Orion spacecraft. The capsule-like Orion will ferry humans into space, provide emergency abort capabilities, and provide safe re-entry for astronauts traveling home from space.



*This rendering shows the conceptual CubeX spacecraft, which would demonstrate X-ray navigation during its mission investigating the Moon. (Image Credit: Harvard University)*

Mitchell said NASA's Deep Space Gateway, a new space station concept that would orbit the Moon rather than Earth, and the Deep Space Transport, intended to carry a crew of four astronauts on 1,000-day trips to Mars and back, also could employ XNAV capabilities.

## CubeX: Characterizing the Lunar Surface

And in another development, the SEXTANT team is working with Suzanne Romaine, a scientist with the Smithsonian Astrophysical Observatory, and JaeSub Hong, a researcher with Harvard University, to fly XNAV on a CubeSat mission called CubeX.

"This is a push to move the technology into the operational mode," said Mitchell, who, along with Gendreau, is a CubeX collaborator. "This is great opportunity for XNAV and showing its value to navigating in deep space."

As currently conceived, the small satellite would gather timing data from the list of SEXTANT millisecond pulsars using CubeX's miniature X-ray telescope. An onboard algorithm would then use the data to determine the spacecraft's trajectory. The team would compare CubeX's solution against that provided by NASA's Deep Space Network, a communications and navigational capability used by all NASA deep-space missions.

Demonstrating XNAV on an operational satellite, however, isn't the mission's only objective.

The other half of its mission, which involves other Goddard scientists, will be spent measuring the composition of the Moon's lower crust and upper mantle to understand the origin and evolution of Earth's only natural satellite, which scientists believe may have formed when a huge collision tore off a chunk of Earth.

"There's a lot we don't know about the Moon. Many mysteries remain," said Hong. A better understanding of the mantle layer could be key to determining how the Moon and the Earth formed. To get this information, CubeX would use a technique called X-ray fluorescence, or XRF.

XRF, which is widely used in science and industry applications, is based on the principle that when individual atoms in sediment, rocks, and other materials are excited by an external energy source — in this case, X-rays emanating from the Sun — they emit their own X-rays that exhibit a characteristic energy or wavelength indicative of a specific element. This can be likened to how fingerprints can identify a specific person.

By capturing these "fluorescing" photons with a miniaturized X-ray optic and then analyzing them with an onboard spectrometer, scientists can discern which elements make up outcrops of the Moon's rocky mantle, which have been exposed by impact craters, and its crust, which overlays the mantle.

The mission would launch no earlier than 2023 to take advantage of the next solar maximum, which would assure a steady bombardment of high-energy X-rays to produce the fluorescence. ❖

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# Goddard Comes A Long Way

*Four Teams Receive Funding Under New Frontiers Competition*

New Frontiers mission-study selections thrilled Goddard planetary scientists who believe the center has come a long way in this hyper-competitive field.

In the running as NASA's next $1 billion New Frontiers mission are the Comet Astrobiology Exploration Sample Return, or CAESAR, and Dragonfly. The agency is expected to choose between the two in mid-2019. Though not selected as finalists, NASA also awarded technology-development funds to the Enceladus Life Signatures and Habitability (ELSAH) and the Venus In situ Composition Investigations (VICI) teams.

> *"Overall, this is a spectacular win for the Goddard team and an acknowledgement of the quality of science Goddard is committed to pursuing."*
>
> ***– Chris Scolese, Goddard Center Director***

Like the finalists, they, too, involve Goddard personnel and mission-enabling capabilities.

Although Goddard has contributed instruments and technology to almost every planetary mission, only in recent years has it played a more visible role conceiving and managing larger-class exploration missions, said Goddard scientist Brook Lakew, the associate director for planning and research and development in the Solar System Exploration Division. "This is a success story for planetary instrumentation at Goddard, and, in particular, the Internal Research and Development

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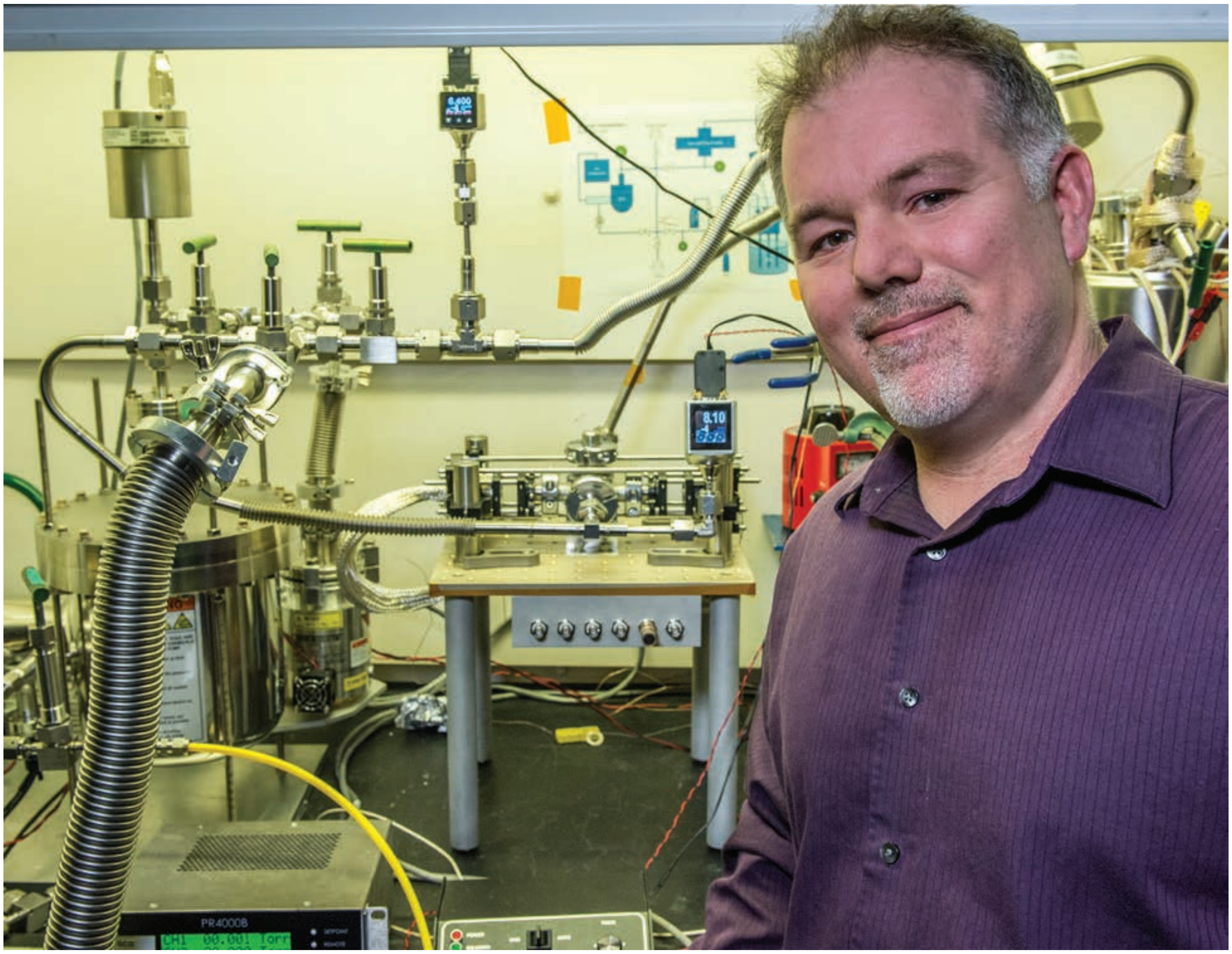

*CAESAR Project Scientist Danny Glavin and others on his team are using R&D funding to advance a gas-transfer system and a water-vapor sensor for this possible New Frontiers mission. CAESAR would gather a sample from a comet and return it to Earth for in-depth analysis.*

(IRAD) program, which has helped mature these mission concepts and many of the instruments that would fly on them."

## CAESAR: Grabbing a Comet Sample

While led by Cornell University Professor Steve Squyres, Goddard would manage CAESAR and provide a couple important technologies if NASA selects it. The principal objective is to send a spacecraft to Comet 67P/Churyumov-Gerasimenko and scoop up nearly three ounces of material. CAESAR's instruments would then separate the volatiles — the ices and other constituents that could evaporate — from the solids, and deliver via parachute a capsule containing the samples to the Utah Test and Training Range.

*"Comets preserve materials from the birth of the solar system and were a major source of the Earth's oceans and the organic molecules that helped give rise to life. Analysis of the CAESAR sample using state-of-the-art laboratory instruments will provide orders-of-magnitude improvements in our understanding."*

***– Steve Squyres, Professor, Cornell University***

"CAESAR would be the first mission to return a sample from the nucleus of a comet," Squyres said. "Comets preserve materials from the birth of the solar system and were a major source of the Earth's oceans and the organic molecules that helped give rise to life. Analysis of the CAESAR sample using state-of-the-art laboratory instruments will provide orders-of-magnitude improvements in our understanding."

No one suggests this would be easy. After "kissing" the comet and gathering the sample, CAESAR would have to transfer the solid material to a sealed sample-containment system, heat the canister slowly to sublimate ices in the sample, and transfer the gases to a separate container — all without melting the water ice contained in the sample. "This is a challenge," said CAESAR Project Scientist Danny Glavin. "The process has to be autonomous and the gas transfer done slowly. We never want to expose the solid sample to liquid water."

To get a head start on the challenge, Glavin and Goddard technologist Jay Parker received IRAD awards to lay the groundwork for a sample-acquisition, transfer, storage, and monitoring system, which would also include a gas sensor to monitor the partial pressure of water vapor.

## Dragonfly: The Rotorcraft Lander

The Dragonfly mission, led by Elizabeth Turtle from

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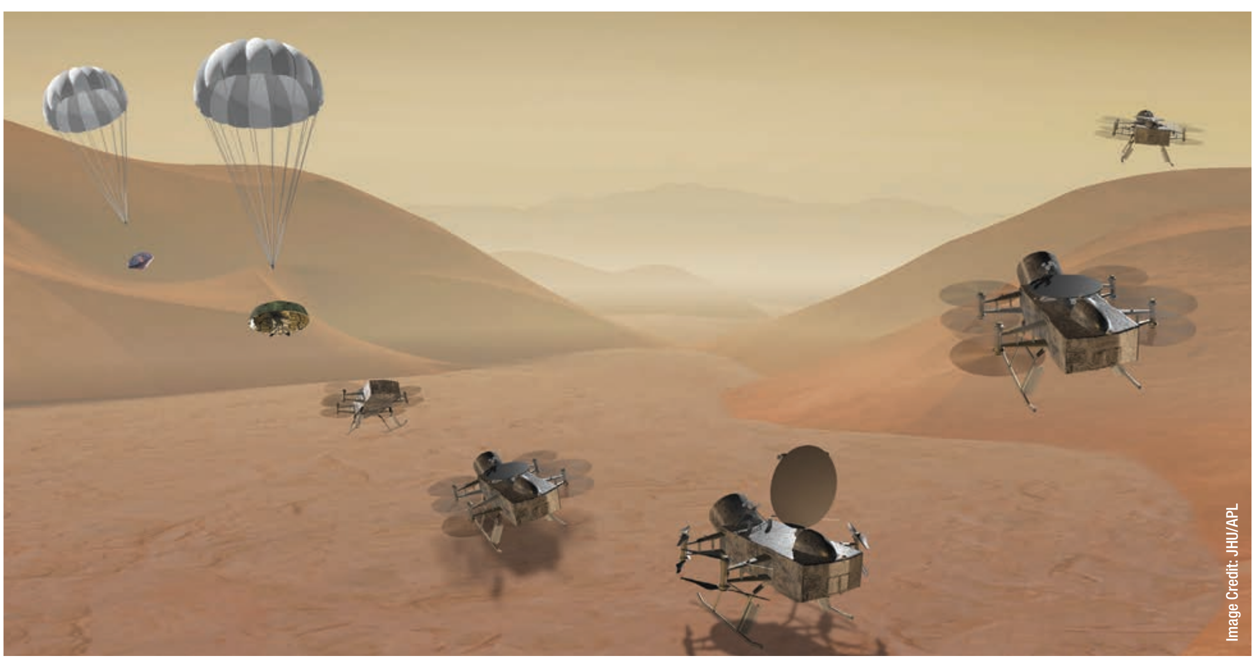

Image Credit: JHU/APL

*One of two finalists in the New Frontiers competition — Dragonfly — would investigate the prebiotic chemistry and habitability of multiple sites on Saturn's moon, Titan. This artist's rendering shows how the Dragonfly rotorcraft would navigate.*

the Johns Hopkins University Applied Physics Laboratory (APL), also is ambitious. This odd-looking craft, which "looks like a rover on skids," would investigate the prebiotic chemistry and habitability of dozens of sites on Saturn's moon, Titan. Powered by plutonium, Dragonfly would be able to fly tens or hundreds of miles to study a variety of terrains, including dunes, impact craters, and possibly its lakes and seas.

> *"The timing couldn't be better, either. It takes advantage of technological advances in drone technology and autonavigation — technologies that we can leverage for planetary science."*
>
> ***– Melissa Trainer, Goddard Scientist***

Among other instruments, it would carry a Goddard-developed mass spectrometer. This instrument would identify the chemical components on the surface and the processes that produce biologically relevant compounds. Goddard also is providing the electronics and neutron generator for an APL-provided gamma-ray spectrometer, which would detect individual elements up to a foot beneath the surface, saidAnn Parsons, the Dragonfly co-investigator who advanced the neutron generator (*Goddard Tech Trends,* Summer 2009, Page 6).

"Dragonfly is really new and innovative," said Melissa Trainer, a Goddard scientist and lead for the mass spectrometer. "The timing couldn't be better, either. It takes advantage of technological advances in drone technology and autonavigation — technologies that we can leverage for planetary science."

## ELSAH: Contamination-Control Techniques

ELSAH would also use a Goddard-developed mass spectrometer to study the plumes coming from about 100 sites on Enceladus, a small but geologically active moon that could harbor an ocean beneath its icy crust. Since NASA's Cassini mission discovered the plumes, scientists have wondered if this strange world hosts an environment suitable for life. ELSAH was conceived to help answer that question.

With the technology-development funding, the Ames Research Center-led team will advance contamination-control technologies for life-detection missions.

"It's fair to say that the OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer) team has done a good job with contamination control, but OSIRIS-REx isn't a life-detection mission," said ELSAH Project Scientist Jen Eigenbrode. "We have to fly technologies that are more rigorous during all phases of the mission." Whatever the team matures likely will be applied to all future life-detection missions, she added. "This will put us in a leadership position. It is a big deal."

## Venus: The Story of Two Landers

The VICI team, led by Goddard scientist Lori Glaze, proposed to deploy two landers to Venus where they would analyze the planet's thick atmosphere, photograph the terrain, and sample the composition of the planet's forbidding surface. Her team will use NASA's technology-development funding to further mature a camera that the Los Alamos National Laboratory would build.

"The overall VICI mission design benefited from IRAD investment," Glaze said. "In fact, NASA liked the design so much that it was willing to invest in the concept. This is good news for us." ❖

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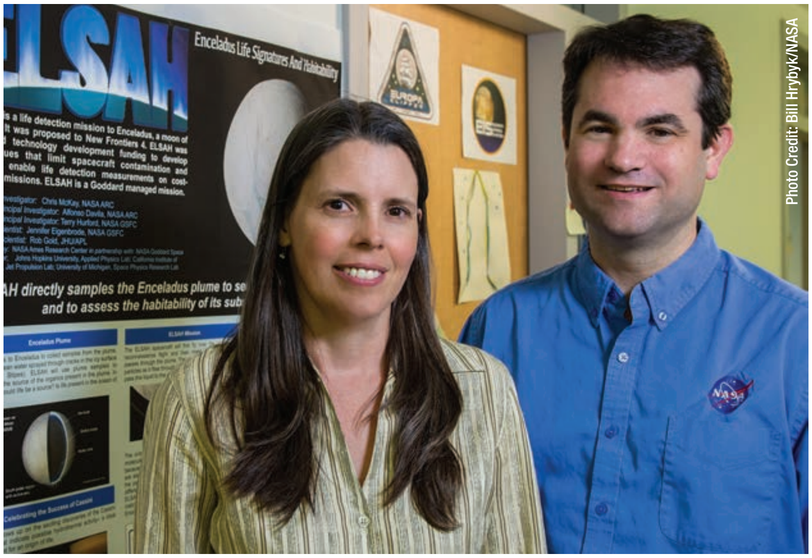


Photo Credit: Bill Hrybyk/NASA

*Jen Eigenbrode and Terry Hurford are part of a team that proposed ELSAH under NASA's New Frontiers competition. Though not selected as a finalist, the team received technology-development funds to advance contamination-control technologies.*

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# Highly Versatile Carbon-Nanotube Technology Eyed for Different Instrument Applications

A decade ago, former Goddard optical engineer John Hagopian began advancing an ultra-dark coating comprised of nearly invisible shag rug-like strands made of pure carbon. He believed the nanotechnology would benefit space science.

He was right: the technology is proving to be highly versatile for all types of spaceflight applications.

In the most recent application of his carbon-nanotube coating, Hagopian, now a Goddard contractor, is collaborating with Goddard scientist Lucy Lim to grow an array of miniscule, button-shaped bumps of multi-walled nanotubes on a silicon wafer. The dots, which measure only 100 microns in diameter — roughly the size of a human hair — would serve as the "ammunition" source for a mini-electron probe. This type of instrument analyzes the chemical properties of rocks and soil on airless bodies, like the Moon or an asteroid.

Although the probe is still early in its technology development, it's showing promise, said Lim, who is using funding from NASA's Planetary Instrument Concepts for the Advancement of Solar System Observations Program to advance the concept.

## The Nanotech-Sized Electron Gun

Key to Lim's instrument, of course, are the carbon nanotubes. Discovered in 1991, these structures exhibit an array of useful electronic, magnetic, and mechanical properties. Among these is their ability to conduct heat and electricity far better than copper can.

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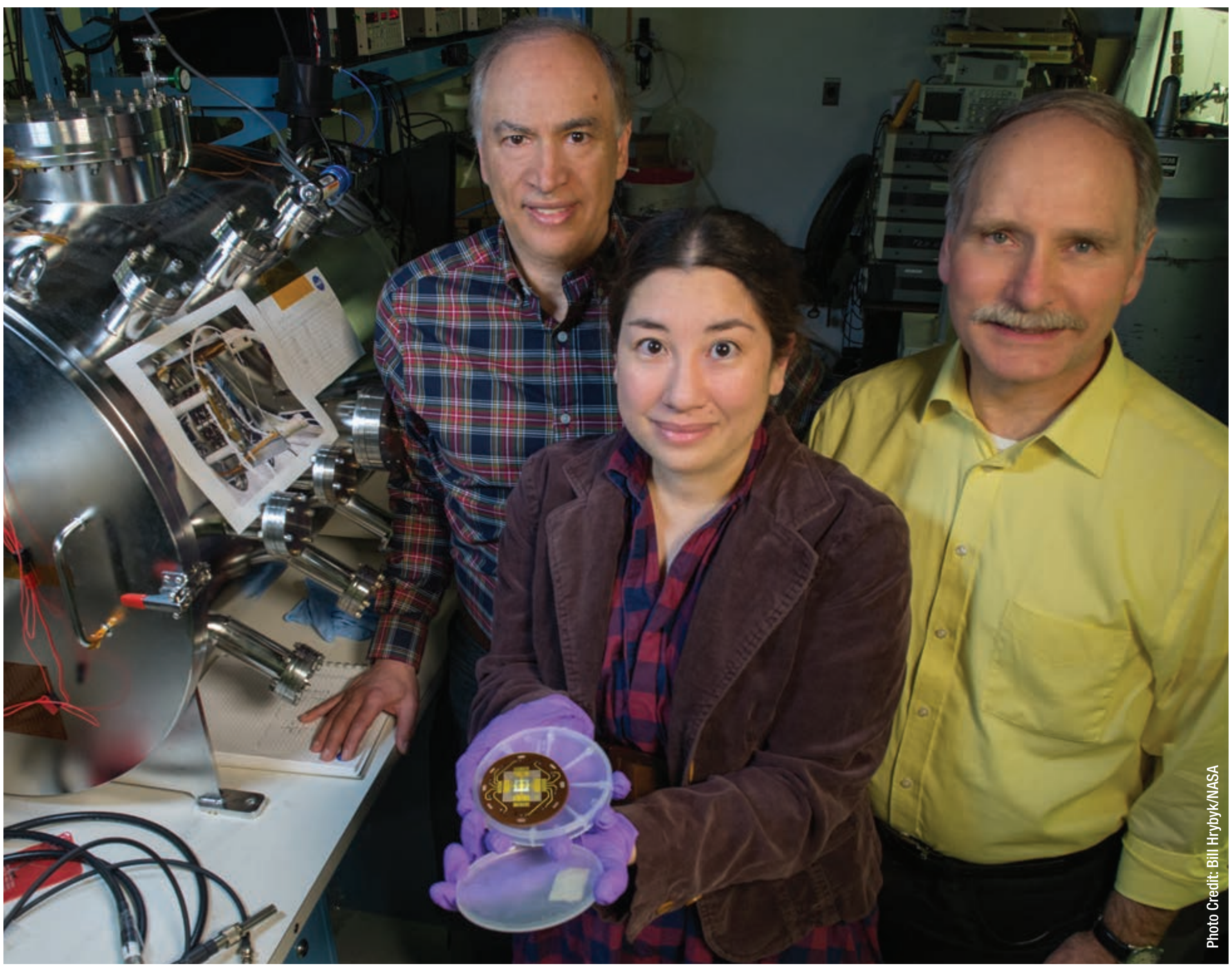

Photo Credit: Bill Hrybyk/NASA

*John Hagopian (left) collaborated with instrument scientist, Lucy Lim, to develop a new instrument that relies on carbon nanotubes to provide the electrons needed to excite minerals contained in an extraterrestrial sample. Larry Hess (right) patterns all the leads and patches where the catalyst for growing nanotubes is deposited.*

To create these highly versatile structures, technicians place a silicon wafer or some other substrate inside a furnace. As the oven heats, they bathe the substrate with a carbon feedstock gas to produce the thin coating of nearly invisible hair-like structures.

For Lim's probe, Hagopian is using this technique to grow tiny, circular dots of carbon nanotubes in a grid pattern that Goddard's detector branch fashioned using photolithography. Positioned above and below the lattice of dots are silicon wires or traces and a grid that produce two different voltages. These voltages create an electrical field that activates the release of electrons contained within the carbon-nanotube bumps or forests.

Under Lim's instrument concept, the electron beams would then pass through a stack of electrostatic lenses to accelerate their speed and help focus them on an extraterrestrial target. When the electrons hit the sample, the bombardment would excite the elements contained within the sample, producing X-rays that a spectrometer would analyze to identify the sample's chemical make-up.

Although NASA has flown other instruments that analyze samples using X-rays, Lim's concept and her use of carbon nanotubes could offer significant improvements.

What's different about her electron field emitter is its small size and the fact that it's fully addressable. "We would be able to choose which bump to activate," Lim said. "We would be able to analyze different spots on the sample individually."

In contrast, if the instrument had only one electron source, it could only analyze one portion of the sample. "We want to obtain compositional maps," she said. "Without the addressable emitter, we might not discover all the minerals contained within a sample, how big they are, or their relationship to each other."

In testing, Lim has demonstrated that the bumps emit enough electrons to excite a sample. Furthermore, Hagopian, who flew a couple coating samples on the International Space Station in 2014 (CuttingEdge, Fall 2014, Page 12), has proven the technology can survive an excursion into outer space.

The team, which also includes Larry Hess with Goddard's Detector Branch, is closing in on the technical challenges and knows the nanotechnology works as envisioned. However, obstacles remain, said Hago-

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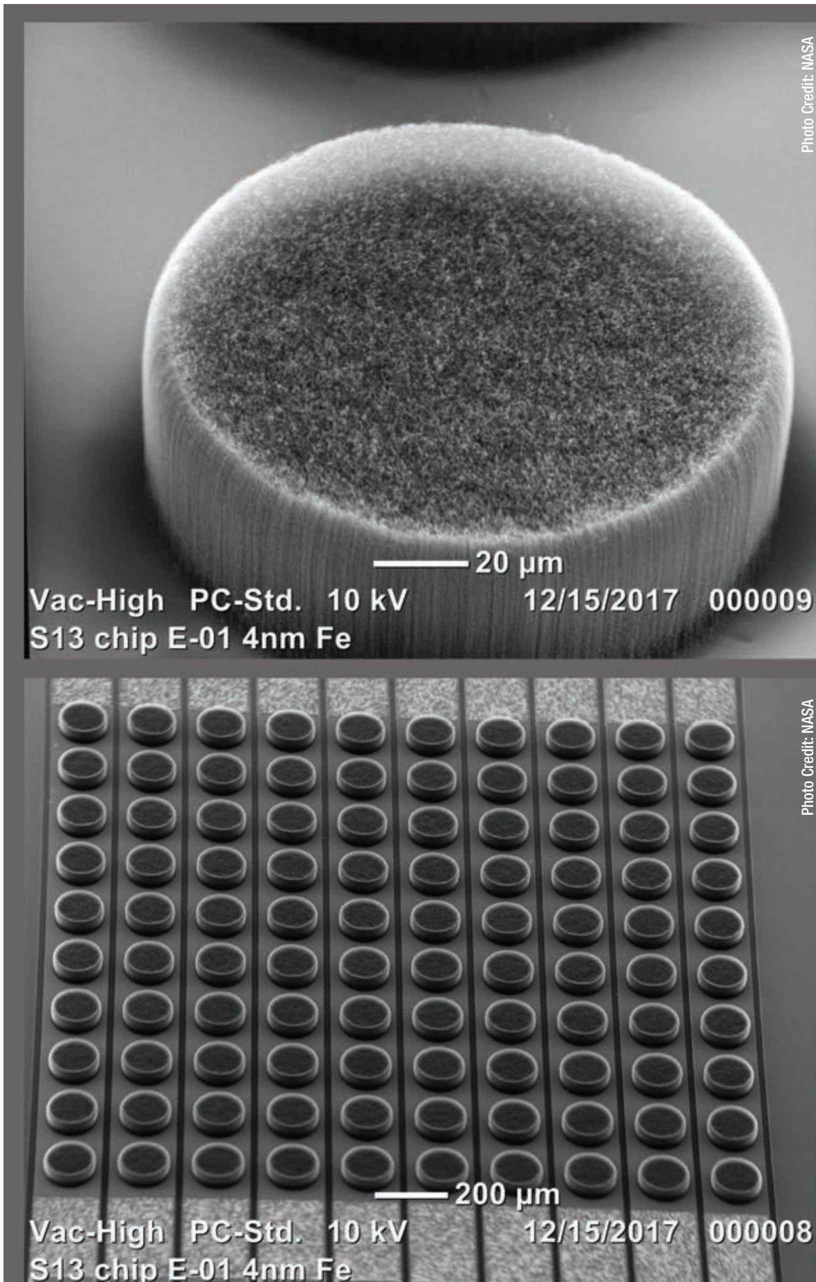


*These images, taken with an electron microscope, show the patterned nanotubes that would operate as electron emitters in a new instrument now being developed for analyzing extraterrestrial samples. The top image is a close-up of one of the bumps.*

pian, the founder of the Lanham, Maryland-based Advanced Nanophotonics. Packaging the nanotube-based grid into a tiny package and then hooking it up to the instrument's electronics "is difficult," Hagopian said. However, the team believes it can demonstrate the nanotube-based electron probe within a couple years under the NASA-funded research effort.

## Straylight Suppression

In a completely different application and one that perhaps is better known, Hagopian is developing coatings to absorb straylight that can ricochet off instrument components and ultimately contaminate measurements.

In testing, carbon-nanotube coatings have proven highly effective at absorbing 99.8 percent of the light that strikes them and is the reason why they appear very black. When light penetrates the nanotube forest, tiny gaps between the tubes prevent the light from bouncing. However, these gaps don't absorb the light. The light's electric field excites electrons in the carbon nanotubes, turning light to heat and effectively absorbing it, Hagopian said.

For researchers at the Space Telescope Science Institute in Baltimore, Maryland, Hagopian's company is growing intricately patterned nanotubes directly onto a component that changes the pattern of light that has diffracted off the edges of telescope structures using coronagraphic masks, which block starlight, Hagopian said. NASA's Small Business Innovative Research program has funded the effort. (See related story, page 2).

He is also collaborating with Principal Investigator Antonio Mannino to create a coating that would prevent straylight from contaminating measurements gathered by a new instrument called the Coastal Ocean Ecosystem Dynamics Imager (COEDI). This hyperspectral spectrometer is being designed to monitor ocean color from geostationary orbit — measurements that scientists and others could use to assess and manage coastal resources.

"I started working with John (Hagopian) two years ago when I discovered in testing that straylight was going to be a problem with COEDI," said Mannino, who is developing his instrument also with NASA R&D funding. "We asked him to help us with the problem. I think he's close to solving it." ❖

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Cutting edge Goddard's Emerging Technologies

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