National Aeronautics and Space Administration

# Cutting edge

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Goddard's Emerging Technologies

## Back to the Future

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# Back to the Future

*Serviceable Spacecraft Make a Comeback; Goddard Technologists Find Solutions*

Ever wonder about the future of space science? Hop inside a time machine that transports you back 40 years and you may get a good idea about where things are headed. History, it would seem, has a funny way of repeating itself.

Serviceable spacecraft — like the NASA-developed Multi-Mission Modular Spacecraft (MMS) and, of course, the iconic Hubble Space Telescope that NASA conceived and developed in the 1970s with servicing in mind — are once again de rigueur. (The serviceable MMS shouldn't be confused with NASA's Magnetospheric Multiscale mission, which also goes by the MMS acronym.)

Case in point: As required by Congress in a law passed in 2010 and then amended 5 years later, NASA is requiring that proposed flagship astrophysics missions support servicing, even if their orbits are up to a million miles away. The agency also released a Request for Information (RFI) seeking ideas for a spacecraft design that it could use for both its proposed Asteroid Redirect Mission (ARM) and as a vehicle for refueling a government satellite in low-Earth orbit.

"The 40-year cycle is starting all over again," said Benjamin Reed, deputy project manager of Goddard's Satellite Servicing Capabilities Office (SSCO), whose personnel developed all of the technologies to service Hubble and is now creating and demonstrating next-generation servicing technologies, including validation experiments on the International Space Station. "It worked with Hubble. It would be crazy not to think it would work again. It's back to the future."

And according to him, NASA is well along the way to realizing that future — even if it means servicing spacecraft positioned tens of thousands of miles away from terra firma.

## What's Different Today

Satellite servicing certainly isn't new — as evidenced by the five Hubble servicing missions and the 1984 repair of the Solar Max mission that used the MMS serviceable satellite bus.

What's different today is where these operations are expected to occur in the future and the technology needed to ensure success. Robotic spacecraft — likely operated with joysticks by technicians on the ground — would carry out the hands-on maneuvers, not human beings using robotic and other specialized tools, as was the case for the low-Earth-orbiting Hubble and Solar Max.

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## About the Cover

Within a black-walled facility at Goddard, SSCO roboticist Stephen Roderick uses industrial robots and mock-ups to simulate interactions between objects in space – a critical component of satellite servicing.

Photo Credit: Chris Gunn


*Goddard engineer Michael Kienlen (left), who is studying servicing beyond low-Earth orbit, and Benjamin Reed, deputy project manager of Goddard's Satellite Servicing Capabilities Office, stand in front of a mockup of the Robotic Refueling Mission now deployed on the International Space Station.*

"Goddard knows how to service satellites in low-Earth orbits," said Michael Kienlen, an SSCO engineer who is studying servicing beyond low-Earth orbit. "However, future flagship missions, including the WFIRST-AFTA (Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets) and other future observatories should operate in more distant orbits."

WFIRST-AFTA, which NASA plans to equip with an 8-foot (2.4-meter) mirror and a slitless spectrometer and imager, will study dark energy, the mysterious form of energy that permeates all of space and accelerates the expansion of the universe, while providing cosmic surveys. It also will carry a coronagraph that will allow the observatory to image giant exoplanets and debris disks in other solar systems.

Other conceptual missions that various groups currently are studying in preparation for the 2020 Astrophysics Decadal Survey also could operate in more distant orbits.

Although still in the conceptual stage, these missions may carry very large primary mirrors that would allow scientists to study cosmological targets with greater resolution and sensitivity. One possible scientific objective would be to find Earth-size exoplanets in the habitable zone in our solar neighborhood and then identify chemicals in their atmospheres that may indicate the presence of life (see related story, page 4).

To achieve these ambitious goals, WFIRST and the other conceptual observatories ideally would operate from Sun-Earth L2 (SEL2), a thermally stable sun-Earth orbit roughly a million miles away.

Due to concerns that technologies might not exist to service SEL2-orbiting missions, some have recommended that the observatories fly in geostationary orbit (GEO), roughly 10 percent of the distance to the moon.

## Robotic Servicing Achievable in SEL2

"GEO may not be an option for these missions because of the thermal-stability requirements,"

*Continued on page 4*

Kienlen said. "One stumbling block is the perception that there is not a plausible scenario for servicing satellites at SEL2. We don't want to force all future flagship missions to a lesser-performing orbit because they are required to be serviceable. So, we will figure out how to take servicing to them."

"It's not like we have to reinvent the wheel. We have never stopped developing servicing technologies. The difference today is that future flagship missions are required to be serviceable," added Julie Crooke, a Goddard engineer, astrophysics technical manager, and member of a team that has been studying one of several future mission concepts. "With appropriate technology investments, we are on a clear path to demonstrating a servicing capability far from low-Earth orbit," she said.

Beth Keer, who heads SSCO's Advanced Concepts Office, agrees. "We have demonstrated robotic refueling on the space station. It's one of the stepping stones along the way to making robotic servicing the way of the future."

## Robotic Refueling

Now in the second phase of its on-orbit demonstration aboard the International Space Station, NASA's Robotic Refueling Mission (RRM) is using the Canadian Space Agency's two-armed robotic handyman, Dextre, to show how future robots could service and refuel satellites in space.

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# Innovative Planet-Finding Technology Passes Another Hurdle

### *VNC Now Sensitive to Broader Spectral Range*

A potentially revolutionary instrument now being developed to first find Earth-like planets in other solar systems and then study their atmospheres to identify chemical signatures of life has just passed another technological hurdle that makes it an even stronger contender for a future astrophysics mission.

The instrument, called the Visible Nulling Coronagraph (VNC), combines an interferometer with a coronagraph — in itself a first. It's well on its way to demonstrating operations over a broader spectral range, including the ultraviolet, visible, and near-infrared bands, said Brian Hicks, a fellow with NASA's Postdoctoral Program who is working with VNC Principal Investigators Rick Lyon and Mark Clampin.

"The VNC is demonstrating the spectral range needed for planet characterization," Hicks said. "It will be more sensitive for finding fainter planets. It also will enable spectroscopy, which is what NASA will need to study the atmospheres of exoplanets to identify signatures of water, oxygen, carbon dioxide, methane, and ozone — the chemistry we associate with habitability for life as we know it."

Currently, the Kepler Observatory uses indirect means to detect exoplanets, as will the James Webb Space Telescope and the Transiting Exoplanet Survey Satellite in the future.

However, many in the scientific community endorse a more advanced mission. They believe NASA's next-generation observatory should come equipped with a super-size primary mirror — possibly as large as 30-feet in diameter — and highly sophisticated instruments, including a coronagraph or occulting star shade that would block starlight and allow the observatory to directly detect and image faint Earth-like exoplanets (see related story, page 2).

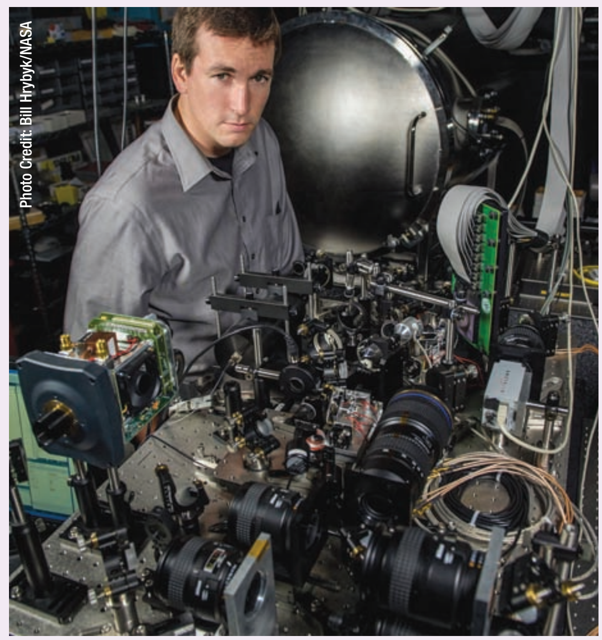

Photo Credit: Bill Hrybyk/NASA

*Brian Hicks stands next to the latest incarnation of the Visible Nulling Coronagraph that improves the spectral performance of the potentially groundbreaking instrument for detecting and characterizing exoplanets. The vacuum chamber is seen behind the breadboard design.*

The VNC, which Clampin and Lyon started developing nearly 6 years ago, specifically is being developed for this task.

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Photo Credit: Chris Gunn/NASA

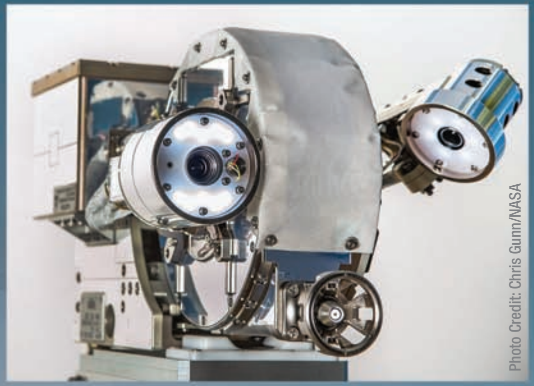

Photo Credit: Chris Gunn/NASA

**ABOVE**

*VIPIR, short for Visual Inspection Poseable Invertebrate Robot, is a robotic, articulating borescope that would help mission operators who need robotic eyes to troubleshoot anomalies, investigate micrometeoroid strikes, and carry out teleoperated satellite-repair jobs. NASA successfully demonstrated VIPIR's capabilities earlier this year.*

**LEFT**

*Beth Keer, the manager of SSCO's Advanced Concepts Office, stands in front of a mockup of ROSE, the Reconfigurable Operational spacecraft for Science and Exploration.*

One of those servicing tools, VIPIR, short for Visual Inspection Poseable Invertebrate Robot, is a robotic, articulating borescope equipped with a second motorized, zoom-lens camera that would help mission operators who need robotic eyes to troubleshoot anomalies, investigate micrometeoroid strikes, and carry out teleoperated satellite-repair jobs. NASA successfully demonstrated VIPIR's capabilities earlier this year. During RRM's third phase, the SSCO team plans to demonstrate the transfer of xenon, a colorless, dense noble gas potentially useful for powering ion engines.

RRM, however, is only one piece of SSCO's ongoing efforts to make servicing a tried-and-true capability for future missions.

## ROSE and Restore

To be easily serviceable, regardless of its orbit, the satellite itself must be specially designed to accommodate repairs. For example, NASA's MMS serviceable satellite bus featured a modular design that made it easy for astronauts to install a new attitude control system when the original failed on Solar Max.

Though not modular like MMS, Hubble did support on-orbit servicing on a component level. Like opening a door, astronauts literally would pull out an instrument before reinserting the new one into the same cavity — a job made easier with the observatory's 76 handholds. However, Hubble's lack of modularity meant that NASA had to develop special tools and procedures specifically for nearly every component and task.

"Although Hubble servicing was extremely successful, the missions were complex and required a highly orchestrated combination of robotic and astronaut activities," observed Dino Rossetti, of Conceptual Analytics in Glen Dale, Maryland, in a paper submitted at an American Institute of Aeronautics and Astronautics conference in September.

Modularity is key, and SSCO is taking it to a new level, Keer said.

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The organization now is developing the Reconfigurable Operational spacecraft for Science and Exploration (ROSE), a low-cost spacecraft concept that seeks to build on the success of MMS. The organization's overriding goal is long-term affordability and servicing at a system level, which would make ROSE highly flexible for medium-size missions, Keer said.

"We view ROSE as a pathfinder for future missions," Reed added.

## Repair Craft Needed

Also needed is a robotic servicing vehicle. Reed said his organization has focused on developing that capability, as well. For the past few years, the organization has pursued a notional mission called Restore, which would be capable of refueling satellites in both geostationary and low-Earth orbits.

Key servicing technologies, he said, are baselined for NASA's proposed asteroid mission, ARM, which involves the capture of a large boulder from the surface of a near-Earth asteroid and moving it into a stable orbit around the moon for astronaut exploration. The same type of spacecraft also could refuel a government satellite in low-Earth orbit, as called for in NASA's RFI.

"I can imagine a fleet of Restores," Reed said. "A single servicer could refuel and service WFIRST and other future observatories at the SEL2 orbit. Another could be parked in another orbit for other servicing tasks, such as helping assemble a 65-foot segmented mirror in space, he said.

"We're taking all we learned over the past many years, robots and humans working together," Keer added. "Our attitude here is you have to have one foot in the future. We expect to be on the cutting edge. Servicing at more distant orbits, such as SEL2, is coming," she said. ❖

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## Planet Finding, *continued from page 4*

Furthermore, its pupil-based technique for separating star from planet light makes it ideal for use with segmented or arbitrarily shaped telescope mirrors, such as the deployables proposed in these potential, next-generation missions. As with the Webb Observatory, the primary mirrors now being considered for these concepts would fold up and then unfurl once the observatories reached their orbital destinations.

Instead of using internal masks and/or an external occulter to block starlight — techniques employed by more traditional coronagraphs — the VNC relies on a two-armed interferometer that splits and then recombines collected light (CuttingEdge, Spring 2012, Page 4). Under this concept, starlight gathered by the observatory's primary, segmented mirror travels down the VNC's optical path to the first of two beamsplitters, which transmits light into one arm and reflects light into the other interferometer arm.

After traversing both arms, the light encounters a second beamsplitter that recombines the light to create two output paths known as the "bright" and "dark" channels. Starlight passes to the bright channel and planet light to the dark.

However, creating these two channels couldn't be possible without a technology called the multiple mirror array (MMA). This device, comprised of 163 tiny individual mirror segments that each measure about the width of six average human hairs and are perched atop tiny finger-like devices that allow them to piston, tip, and tilt up to thousands of times per second, is placed in the interferometer arm that receives reflected light.

The MMA's job is to correct errors. It first senses and then corrects wavefront errors caused by vibration, dust, and thermal changes that prevent the bright starlight, collected by the primary mirror, from being perfectly "nulled" — in other words, ultimately canceled in the dark channel.

A spectrograph and imager then would analyze the dark-channel light to determine the planet's physical properties.

## Rhombs Provide Solution

In testing with the VNC testbed, the technique proved that it could achieve nearly billion-to-one contrast, but over a narrow band in the visible spectrum. "This first milestone still stands as the deepest contrast ever achieved with a nulling coronagraph," Lyon said, adding that this achievement was made possible by engineers Udayan Mallik, who set up all computer interfacing to control the

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Photo Credit: Chris Gunn/NASA

*In this image taken in 2012, Rick Lyon (foreground), Udayan Mallik (left), and Sigma Space's Pete Petrone (right) monitored the progress of wavefront control using the early version of the Visible Nulling Coronagraph that at the time was operating inside a vacuum tank. This version of the instrument proved the VNC concept.*

## Planet Finding, *continued from page 5*

devices, and Pete Petrone, who built the VNC hardware and optics. "It also clearly demonstrated nulling with a segmented aperture — another significant milestone."

The team now is increasing VNC's sensitivity over a broader spectral range needed to detect and characterize Earth-like planets.

The group incorporated two pairs of identical prisms into both interferometer arms. These "squashed" rectangular-shaped, highly polished prisms, known as Fresnel rhombs, produce polarizing reflections — similar to what happens to sunlight that reaches your eyes after reflecting off cars or pavement. "While this scattered light reduces contrast when driving without wearing sunglasses, the polarization effect is actually helpful in the VNC," Hicks said.

"The polarization effect achieved through the rhombs is something that can be used to make starlight suppression with the VNC work at high contrast over a broad spectral range," Hicks said. "Now we are working to demonstrate the instrument with 40 times the bandwidth," he added.

But the addition of the rhombs isn't the only new technology the team is pursuing to cement its possible inclusion in a next-generation mission.

Lyon, Clampin, Hicks, and others on the team won NASA technology-development funds to demonstrate the VNC on an actual segmented optical testbed, called the Segmented Aperture Interferometric Nulling Testbed, or SAINT for short, Lyon said. The work will begin in October.

Goddard engineer Matt Bolcar, Hicks, and Lyon also have won additional NASA funding to investigate the use of freeform optics, an emerging optics technology that allows light-gathering devices to take almost any shape, potentially providing improved image quality over a larger field of view — all in a smaller package (see related story, page 15).

"One of the primary advantages of freeform optics is that they can reduce the total number of elements needed for a flight VNC. Most importantly, this would improve throughput, among other things," Lyon said. "By custom tailoring the shape of the optics, we may achieve a wider field of view."

"Each of these is a significant improvement and could make the VNC a game changer when it comes to designing the future mission that will have characterizing exoplanets as one of its top priorities," Hicks said. "The goal is to use the improvements and the enabling technologies to make the VNC an even better choice for yielding the greatest science return." ❖

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# STORM Leads to a SMILE

*Successful Demonstration of Goddard's First-Ever, Wide-Field Soft X-ray Imager Results in Possible European-Led Mission*

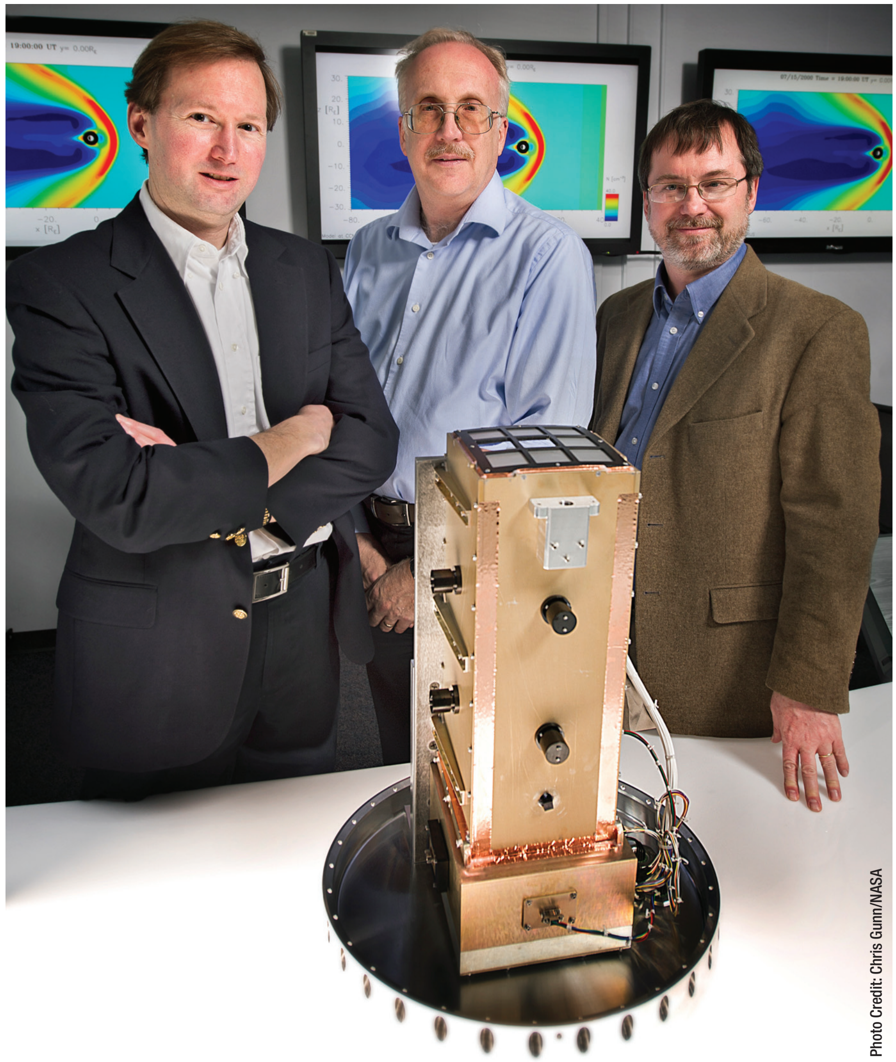

Photo Credit: Chris Gunn/NASA

*Principal Investigators Michael Collier (left), David Sibeck, and Scott Porter created NASA's first wide-field-of-view soft X-ray camera that incorporated a never-before-flown X-ray focusing technology. The instrument, called STORM, has led to a possible European-led mission that will adopt the same measurement technique.*

The successful demonstration nearly 3 years ago of NASA's first wide-field-of-view soft X-ray camera that incorporated a never-before-flown X-ray focusing technology has led to a possible European-led mission that will adopt the same measurement technique.

An instrument similar in concept to the Goddard-developed Sheath Transport Observer for the Redistribution of Mass (STORM) could be used in a multinational mission called the Solar Wind Magnetosphere Ionosphere Link Explorer (SMILE). It will include a wide-field-of-view soft X-ray camera using lobster-eye optics, similar to STORM.

Led by Principal Investigator Graziella Branduardi-Raymont of the Mullard Space Science Laboratory in England, SMILE is being supported by the European Space Agency. The organization plans to launch SMILE in 2021.

## STORM: SMILE's Muse

STORM's sounding-rocket flight aboard a two-stage Black Brant IX from the White Sands Missile Range in December 2012 not only proved the instrument's concept, but also revealed details about "charge exchange," a poorly understood phenomena that happens when solar wind sweeps across the solar system at about a million miles per hour and collides with the uppermost region of planetary atmospheres (including that of Earth) and neutral gases in interplanetary space (*CuttingEdge*, Winter 2013, Page 2).

During the collision, the heavy ions in the solar wind "steal" an electron from the neutrals — an exchange that puts the heavy ions in a short-lived excited state. As they relax, they emit soft X-rays.

"The prototype we developed raised the technology readiness to a level where it can be flown on a major mission," said Michael Collier, the scientist who led a unique interdisciplinary team that built STORM. "SMILE is not a NASA mission. We will not be building the instrument," he said.

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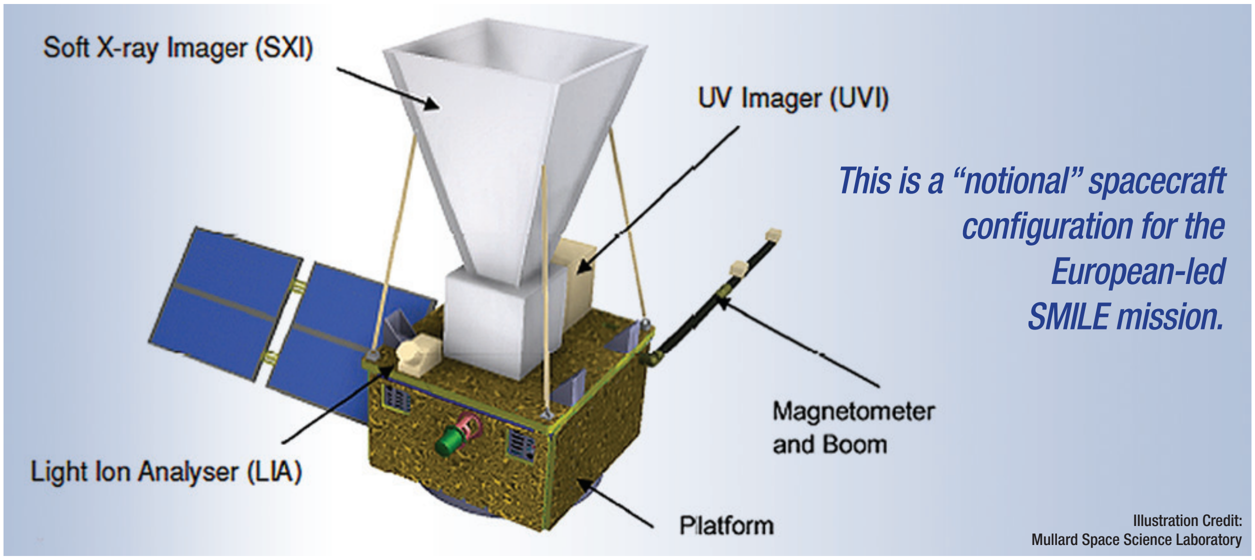


"However, our experience led up to this," added David Sibeck, a Goddard heliophysicist who helped build the instrument, along with Goddard astrophysicist Scott Porter. "We're using our experience to do even greater things here. Frankly, our long-range goal is to further advance STORM for a future mission. We have ideas on how we could do this."

## Three Disciplines Benefit

SMILE and a possible NASA follow-on would satisfy the needs of three scientific disciplines — an unusual occurrence that motivated Collier, Sibeck, and Porter to collaborate in STORM's development in the first place.

Since the discovery of the cosmic charge-exchange phenomena in the mid-1990s, scientists have observed the resulting emission of soft X-rays from comets, interplanetary space, possible supernova remnants, and galactic halos. Planetary scientists have observed soft X-ray emissions from the outer atmospheres of Venus and Mars, leading some to question whether the charge-exchange phenomena that produces the radiation contributes to atmospheric loss on the Red Planet.

Heliophysicists also have observed soft X-rays from the outer boundaries of Earth's magnetosphere, a region particularly sensitive to solar storms that can damage spacecraft electronics, cause spurious readings from global positioning satellites, and knock out satellite-based communications and terrestrial power grids. And astrophysicists have observed them, too — as unwanted noise in data collected by all X-ray observatories sensitive to soft X-rays.

As a result of these observations, planetary scientists and heliophysicists are anxious to measure this emission and astrophysicists want to remove it as noise.

## Lobster-Eye Optics Key

STORM — and more specifically its lobster-eye optics — proved it could give scientists a global view of the phenomena. The optics, which had never been flown until STORM's debut, are so-named because they mimic the structure of the crustacean's eyes, which are made up of long, narrow cells that each captures a tiny amount of light, but from many different angles. Only then is the light focused into a single image.

Pioneered by researchers at the United Kingdom's University of Leicester, a partner in the development of both STORM and SMILE, lobster-eye X-ray optics work the same way. Its eyes are a microchannel plate, a thin curved slab of material dotted with tiny tubes across the surface. X-ray light enters these tubes from multiple angles and is focused through grazing-incidence reflection, giving the technology a wide field of view necessary for globally imaging the emission of soft X-rays in Earth's exosphere.

Although the Goddard team still hopes to develop a NASA mission, for now team members are happy ESA is considering a mission. "Their success is our success," Sibeck said. "The important thing is getting a mission launched." ❖

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# Beach Ball Coronagraph

*Scientist Develops Formation-Flying CubeSat Mission to Study Sun's Corona*

What's better at blocking sunlight: a traditional flat occulter disk or a beach ball?

Goddard scientist Phillip Chamberlin is putting his money on the latter. He now is developing a pathfinding mission that would deploy a never-before-flown tennis ball-size titanium occulter, which would fly in formation with a CubeSat equipped with an imaging spectrograph to study the sun's corona, and more particularly, coronal mass ejections. These gigantic bubbles of charged particles speed across the solar system and can wreak havoc on low-Earth-orbiting satellites and terrestrial power grids when they slam into Earth's protective magnetosphere.


*Principal Investigator Phillip Chamberlin holds a sphere coated in super-black carbon nanotubes.*

In particular, Chamberlin is interested in imaging and measuring the temperature and speeds of electrons that make up these violent outbursts using a technique that has never before flown in space.

## Understanding How the Corona Evolves

This data would improve scientists' understanding of how the corona evolves over time and perhaps what causes the coronal mass ejections, also known as CMEs. "Currently we can't predict them. We don't know the warning signs. We're like weather forecasters 50 years ago," Chamberlin said, adding the mission also could shed light into why the solar corona is orders-of-magnitude hotter than the sun's surface, or photosphere.

Under the concept, called the Spherical Occulter Coronagraph CubeSat, or SpOC, the occulter would block the sun's light — in effect creating an artificial total solar eclipse — revealing the corona, and, of course, the energetic events that take form there.

To carry out this mission, NASA would insert the CubeSat in an Earth-escape orbit starting at about 238,000 miles away. The instrument-carrying mother ship would literally drop the occulter sphere and adjust its orbit via thrusters and navigation technology so that it would fly roughly 7 feet behind the device.

## New Coronagraph Needed

The mission couldn't come too soon, Chamberlin said.

Currently, two spacecraft, the Solar and Heliospheric Observatory, or SOHO, that NASA launched in 1995 and the Solar Terrestrial Relations Observatory, or STEREO, deployed 11 years later, carry flat-plate occulters that block light originating from the photosphere to make visible the sun's corona that otherwise scientists could not see. However, both spacecraft are getting older and NASA currently has no mission planned to

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provide the same coronal observations.

Just as important, Chamberlin said, is the position and shape of the occulter plates used on these missions.

## Snuffing Out the Noise

"Coronagraphs are notoriously noisy," he explained. Diffractive light — in other words, the light that passes around the edge of an object — interferes with the light that the instrument needs to gather. One way to avoid light contamination, he added, is to place the occulter disk as far away as possible from the instrument. In SOHO, the occulter is positioned 2.6 feet from the coronagraph; in STEREO, it sits farther away at 4 feet. In SpOC, however, the distance is nearly double the distance of STEREO's occulter plate at roughly 7 feet.

Furthermore, current research is likely to prove experimentally the theory that spherical occulters are more effective than flat plates at blocking light, Chamberlin said. A case in point is the moon itself, which at least once a year moves into a position between Earth and the sun to create a natural coronagraph, revealing the faint halo of coronal light. "The diffraction isn't concentrated and therefore you get less noise," Chamberlin said.

Enter SpOC's titanium sphere. In addition to the diffraction-suppression advantages of being round, the sphere could prove even more effective at eliminating noise. Chamberlin plans to test the effectiveness of a carbon-nanotube coating, which he would apply to the titanium balls.

This super-black material, comprised of multi-walled nanotubes made of pure carbon, is especially effective at absorbing stray light (*CuttingEdge*, Fall 2014, Page 12). That's because carbon atoms occupying the nested tubes absorb the light and prevent it from reflecting off surfaces. In this case, Chamberlin wants to further reduce scattered sunlight that reflects off Earth and then into the spectrograph.


Photo Credit: NASA

*The inspiration behind a potential next-generation occulter disk is Echo 1, a communications satellite launched in 1960.*

## The Ultimate Goal: A Beach Ball Occulter

The next step, he said, would be to further advance the technologies and compete for a CubeSat mission opportunity that would lay the foundation for a larger, more robust mission — one where he would swap the solid, titanium sphere for a 98-foot diameter (30-meter) inflatable occulter that is more like a giant beach ball.

It's not a far-fetched concept, either, he said. NASA's Langley Research Center designed Echo 1, a 100-foot diameter Mylar-covered sphere that operated as a passive communications reflector for transcontinental and intercontinental telephone, radio, and television signals after its launch from Wallops Flight Facility in 1960. It reentered Earth's atmosphere in 1968.

"SpOC is a pathfinder directly scalable to future Explorer-class coronagraphs, with even larger separations, possibly hundreds of meters using inflatable spherical occulters," Chamberlin said. Such a configuration would more closely resemble nature's most effective occulter — the moon. ❖

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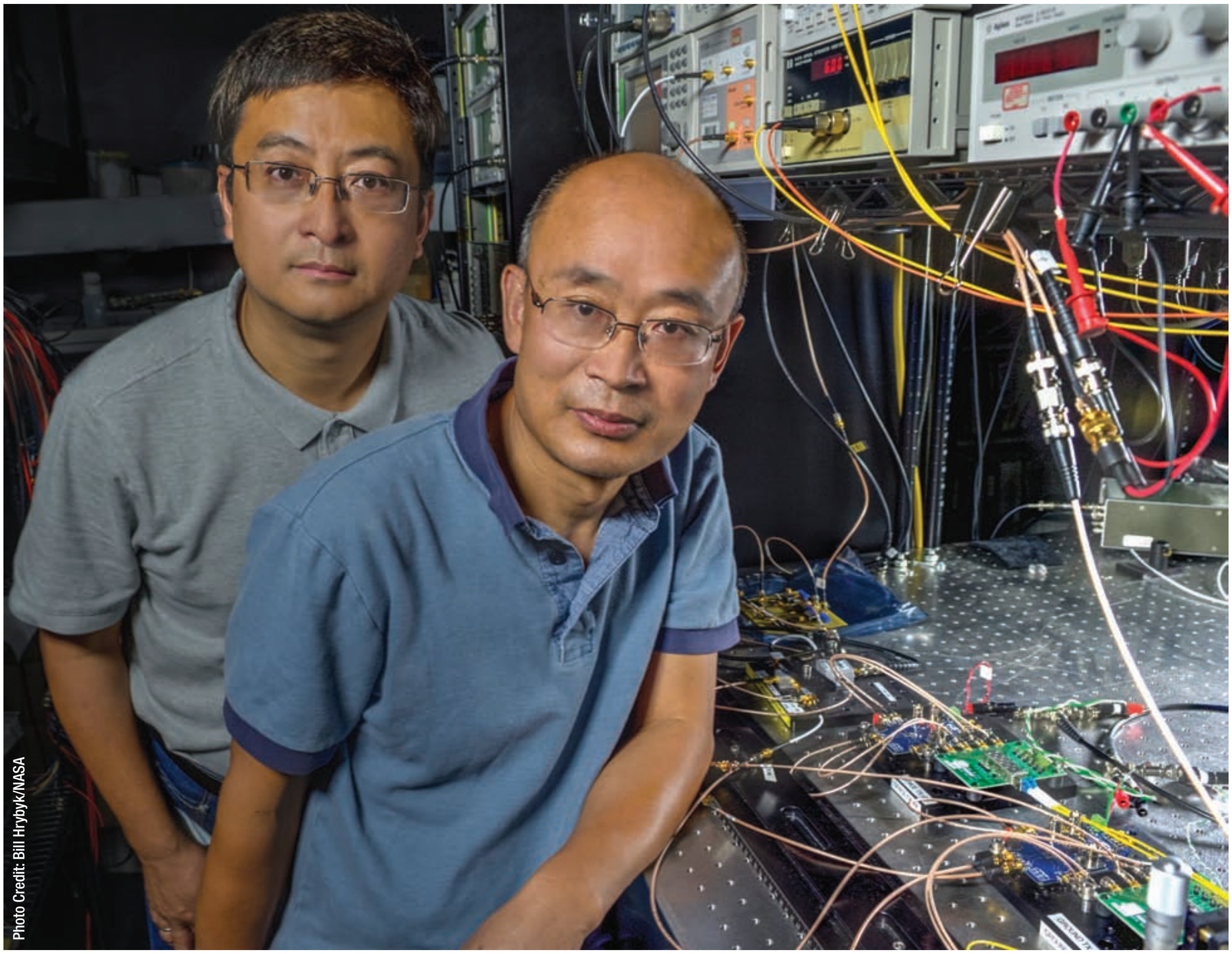
# Lasercom Takes a Step Forward

*Breadboard Optical Communication System Demonstrates New Highs in Accuracy*




*Guan Yang (right) and his research associate, Wei Lu, pose in front of the lasercom breadboard they created to demonstrate high data-rate download and uplink speeds as well as highly precise distance and speed measurements all from the same, relatively small package.*

A Goddard-developed laser communication (lasercom) system made headlines in 2013 when it demonstrated record-breaking data download and upload speeds to the moon. Now, a Goddard optical physicist says he can match those speeds, plus provide never-before-achieved, highly precise distance and speed measurements all from the same, relatively small package.

Called the Space Optical Communication and Navigation System, the breadboard technology made up of commercially available components simulating both ground and space terminals recently showed in laboratory testing that it could provide micrometer-level distance and speed measurements over a 622 megabit-per-second (Mbps) laser communication link.

## Advances in Communications, Navigation, and Science

"Combined with the large communication bandwidth, high-precision ranging over an optical communication network will bring about significant advances in navigation and communications, to say nothing of science gathering, notably in the area of geodesy," said technology developer Guan Yang. And because of its diminutive size, "it also will enable use on CubeSats," an increasingly popular spacecraft bus that typically is no larger than a shoebox.

The ground-based test was similar to one carried out in late 2013 aboard another Goddard-developed lasercom experiment hosted on NASA's

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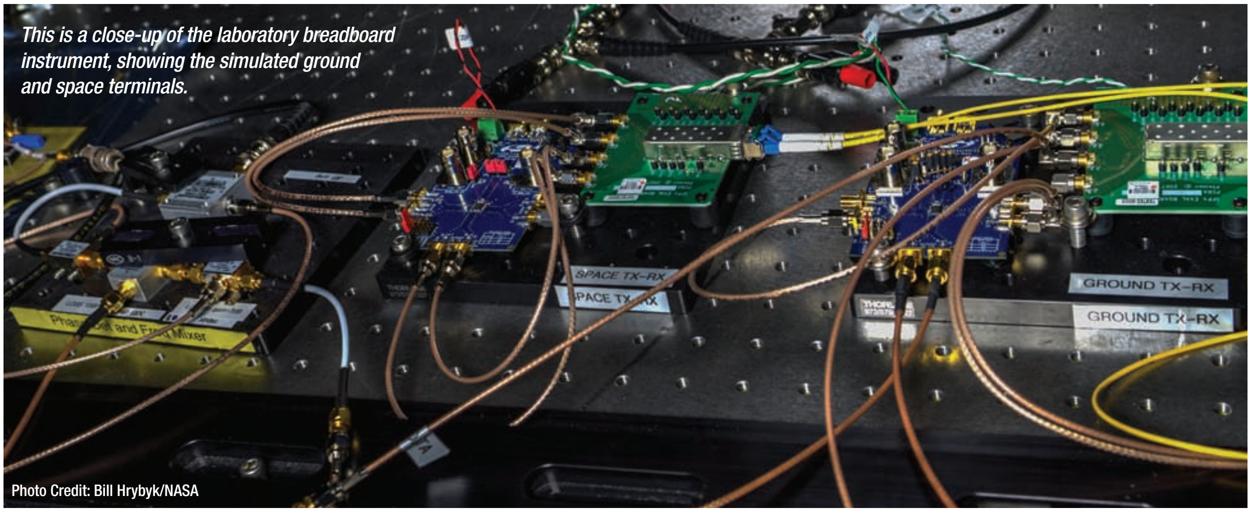


*This is a close-up of the laboratory breadboard instrument, showing the simulated ground and space terminals.*

Photo Credit: Bill Hrybyk/NASA

Lunar Atmosphere and Dust Environment Explorer (LADEE) (*CuttingEdge*, Fall 2013, Page 15).

During the LADEE mission, the Lunar Laser Communication Demonstration (LLCD) downloaded and uploaded data to and from lunar orbit at 622 Mbps and 20 Mbps, respectively, proving that it could operate as well as any NASA radio system. At the time, mission operators said that had they used LADEE's onboard radio system to download one gigabyte of LADEE's stored science and spacecraft data, it would have taken several days to complete the transmission.

But before the LLCD experiment could break the data-transmission records, it needed to know the speed of the LADEE spacecraft as it orbited the moon as well as its distance from the LLCD ground terminals. This required that the high-frequency laser beam that carried the embedded data also obtained highly accurate distance and speed measurements.

It succeeded. LLCD's instrument gathered velocity measurements accurate to within about 10 millimeters per second; its position calculations were accurate to within 12 millimeters.

## Besting LLCD

Yang's new miniaturized lasercom transceiver, however, bested LLCD's accuracy by several orders of magnitude. In addition to transmitting data at LLCD's record-breaking rate of 622 Mbps, it measured speed within an accuracy of less than 10 micrometers per second and distance within 20 micrometers.

The system achieved these unprecedented accuracy measurements by incorporating a Doppler frequency — which can be likened to an ambulance siren that increases or decreases in pitch as the vehicle travels closer or farther away — enabled by a highly specialized computing algorithm, called the Fast Fourier Transform.

"When you're trying to predict where something is, one of the issues is eliminating measurement errors," said Dennis Woodfork, a Goddard assistant chief for technology specializing in navigation and communication technologies. "If errors build too much, you will lose position, and therefore, you won't know where the spacecraft will be in the future. Guan's measurements are at least an order-of-magnitude better. He got great ranging."

Yang agrees. "If you can measure that precisely, you can easily use it for navigation," he said. He envisions its use on a constellation of smallsats flying in an exacting formation to get simultaneous, multi-point observations or as the navigational guide to carry out autonomous rendezvous and docking.

Science also could benefit, he said. Due to its precise pointing and micrometer-level, two-way ranging, he believes the technology is particularly ideal for geodesy, the science of measuring variations in Earth's gravitational field caused by changing land mass. "This system opens a new way for science missions," Yang said.

Although pleased with the test results, Yang now wants to further improve the technology and ultimately fly it on a CubeSat. "The test proved the concept and accuracy. I'm now talking with the science community to find an application. We are targeting a CubeSat opportunity." ❖

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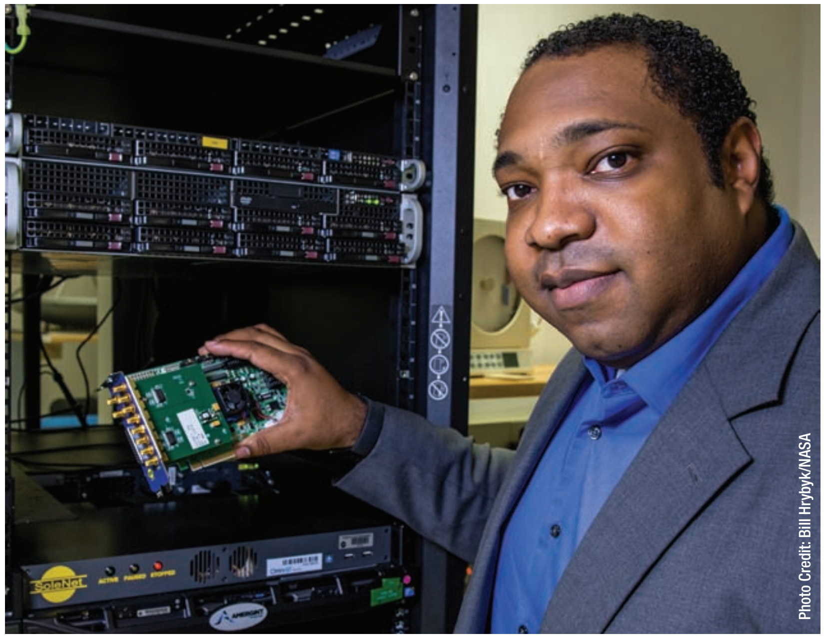
# New System Giving SMAP Scientists the Speed They Need

*Fastest Data Transfer Off Antarctic Continent*

For scientists now studying the voluminous amounts of data collected daily by NASA's Soil Moisture Active Passive (SMAP) mission, speed is everything. A new Goddard-developed data-transmission technology installed at the U.S. Antarctic Program's McMurdo Station in Antarctica is giving them the speed they need.




*Philip Baldwin holds the custom-designed high-speed interface card that enables data transfer from Antarctica to White Sands, New Mexico, at about 300 Mbps. The electronics rack in the background is similar to the one inside the radome housing the new equipment.*

Since SMAP began gathering soil-moisture measurements in the spring, the upgraded McMurdo TDRSS Relay System (MTRS) operating as part of NASA's Near Earth Network (NEN) has transmitted terabytes of data via NASA's Tracking and Data Relay Satellite System (TDRSS) at a whopping 200 megabits per second (Mbps) — a speed that makes typical American broadband speeds of between 10-20 Mbps look more like dial-up Internet service.

SMAP measures the amount of water in the top 2 inches of soil everywhere on Earth's surface, distinguishing between ground that is frozen or thawed. The mission is now producing its global measurements with just its Goddard-developed radiometer instrument after it was found this summer that the SMAP radar could no longer return data.

With the SMAP radiometer data, scientists will produce global maps to improve their understanding of how water and carbon in its various forms circulate. The data also will enhance scientists' ability to monitor and predict natural hazards like floods and droughts. In addition, SMAP data have additional practical applications, including improved weather forecasting and crop-yield predictions.

"The mission is downloading terabytes of data; hence the need for a faster link," explained Systems Engineer Philip Baldwin, who led a six-member team that spent 5 years redesigning and building the system that allows for the fastest data transfer off the Antarctic continent. "Not only do they have a lot of data to downlink, the mission's data also is time-sensitive. We have only 30 minutes to deliver the data from one pass. So far, we haven't lost any data, and SMAP is happy with the service we're able to provide," he said, adding that MTRS is actually capable of 300 Mbps data-transfer speeds.

## Other Polar-Orbiting Spacecraft Will Benefit

Although developed to accommodate SMAP's titanic data and tight time requirements, MTRS eventually will function as an asset under NEN and become available to other polar-orbiting spacecraft. "This will greatly increase Goddard's ability to support an even greater range of science missions," Baldwin added.

The system's performance is striking, Baldwin conceded, adding that it went operational in March when SMAP started gathering data. "It really has improved data flow," he said.

As the polar-orbiting SMAP flies over Antarctica, it downlinks roughly 10 gigabytes of data during each pass to an X-band receiver located at the

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McMurdo Ground Station. (Due to TDRSS visibility, SMAP downloads up to six times a day.)

A fiber-optic cable carries the data to the MTRS equipment housed 1.5 miles away inside an orange and white radome covering the MTRS 4.6-meter antenna dish and the system's high-speed terminal consisting of two boxes or racks of electronic equipment. Every 12-hour period, the data are transferred to a TDRSS spacecraft that then downlinks the data to NASA's Space Network (SN) ground station at the White Sands Complex in New Mexico, for ultimate delivery to SMAP scientists.

To create the capability, the team upgraded an existing system that Goddard initially developed 15 years ago to demonstrate data transfer from McMurdo to White Sands. The previous incarnation of the system was last used in 2005 and had remained dormant since. Among other issues, the existing equipment fell far short of SMAP's operational readiness for data transfer and timing. "We assessed what we needed to do and basically started over," Baldwin said.

The team, which visited Antarctica five times to complete the job, designed, upgraded, and refurbished every aspect of the system, Baldwin said.

Photo Credit: Philip Baldwin/NASA

*The orange-and-white radome that houses the upgraded McMurdo TDRSS Relay System is about 1.5 miles from the actual McMurdo Station, Antarctica.*

It created the software, custom transceivers, and high-speed computers to produce the fastest data link off the world's southern-most continent.

"It's certainly faster than my Internet service at home," he added. ❖

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# Out With the Old, In With the New: Telescope Mirrors Get New Shape

Telescope mirrors of old basically came in one shape: they were round and fit nicely inside a tube. No longer. An emerging optics technology now allows these light-gathering devices to take almost any shape, potentially providing improved image quality over a larger field of view — all in a smaller package.

Called freeform optics, this emerging mirror technology, brought about by advances in computer-controlled fabrication and testing, has triggered a sea change in optical engineering. Seeing the benefit of "potato chip-shape" or asymmetrical optics, Goddard optical engineers have moved quickly to establish an expertise at the center.

## New Group Formed

"The use of freeform optics can significantly reduce the package size as well as improve the image quality," said Joseph Howard, who plans to ultimately design, integrate, and test a two-mirror freeform optical telescope for imaging and spectroscopic applications.

To hasten the learning curve, Howard and his colleague, engineer Garrett West, established a group called the Freeform Optics Research Group Endeavor (FORGE). The group oversees freeform-optics research carried out by private industry under NASA's Small Business Innovative Research program and Goddard scientists and engineers. The group already has implemented freeform-design practices in Goddard's Optical Design Laboratory, known as the ODL, which provides design and engineering for instrument proposal efforts.

Other non-NASA research groups also are studying freeform optics, including the Center for Freeform Optics (CeFO), a National Science Foundation-sponsored cooperative research center headquartered at the University of Rochester and the University of North Carolina-Charlotte. Howard

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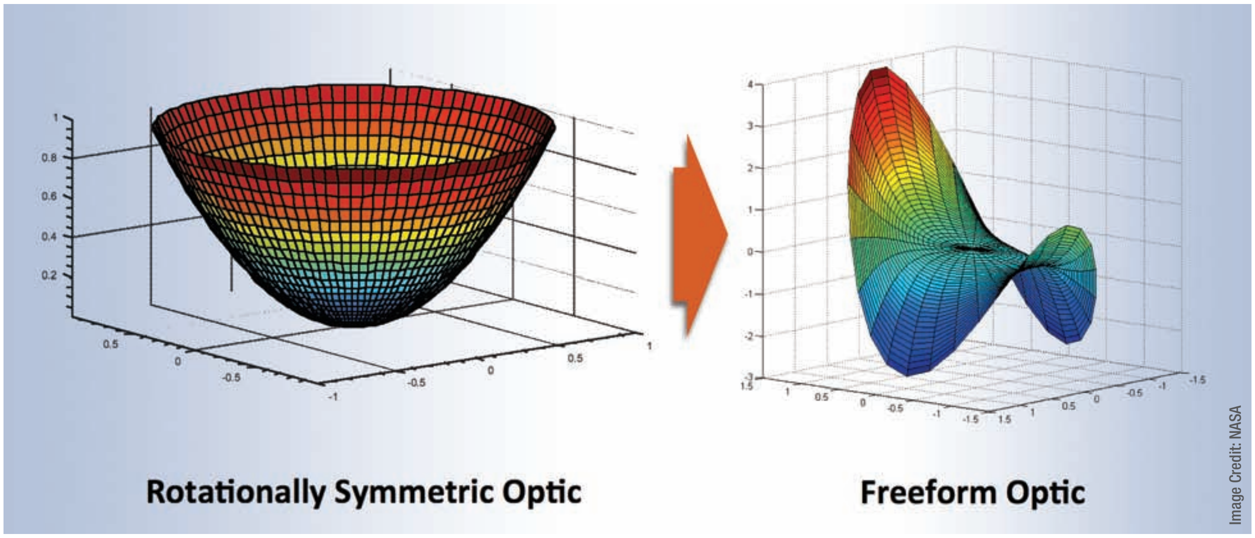


*A rotationally symmetric optic is traditionally used in telescopes. The freeform optic on the right takes a different shape and is now being investigated for use in space-based instruments.*

would like to join CeFO and is discussing possible ways to collaborate on instrument concepts using freeform optics, he said.

## Great Promise

According to both Howard and West, the technology holds great promise for scientists who want to develop compact telescopes for CubeSat and other small satellites — an increasingly popular and cost-effective alternative to more traditional missions that are more expensive to build and launch.

"If you want to put these telescopes into a smaller box, you need to let the mirrors bend like a potato chip," Howard explained.

With traditional two-mirror telescopes consisting of a primary light-gathering mirror and smaller, secondary mirrors, which relay the incoming light and direct it onto a detector, the rotationally symmetric — in other words, round — mirrors need to be aligned along the axis of the system to reduce optical aberrations that produce blurry images.

With freeform optics, however, the asymmetric mirrors can better correct for these aberrations to provide a larger usable field of view, as well as dramatically reduce the light path, or package size.

As part of their research effort, Howard and West recently evaluated the optical system of a coastal measurement instrument, originally equipped with nine symmetrical mirrors. By replacing the mirrors with freeform optics, they were able to reduce the size and number of mirrors to six, shrinking the telescope's overall packaging by more than tenfold.

They also have selected a candidate two-mirror freeform optical telescope design, and are now awaiting the delivery of the two freeform mirrors with which they plan to assemble a prototype instrument for testing. "Our design studies suggest that a factor of five or more reduction in the volume of optical instrumentation can be achieved by freeform surfaces," Howard said, adding that image quality also improves considerably.

Next year, the team plans to continue testing its two-mirror instrument, which includes a freeform mirror manufactured with 3-D printing, also called additive manufacturing. This extends the work of another R&D effort that developed the first imaging telescopes assembled almost exclusively with 3-D manufactured parts (*CuttingEdge*, Summer 2014, Page 8). With this technique, a computer-controlled laser melts material in precise locations as indicated by a 3-D CAD model. Because the mirror will be constructed layer by layer, it will be possible to construct a mirror with any shape.

The team believes the technology could prove to be game changing for a number of future missions, including a new instrument for imaging exoplanets (see related story, page 4). "NASA will benefit," Howard said. "Freeform optics will be critical. They will enable larger fields of view and fit in size-limited packages, such as those found in CubeSats and small satellites, or on larger missions where space allocations are tight," Howard said. ❖

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# Stacked Like a Skyscraper

*Techniques for Cooling 3-D Integrated Circuits Investigated*

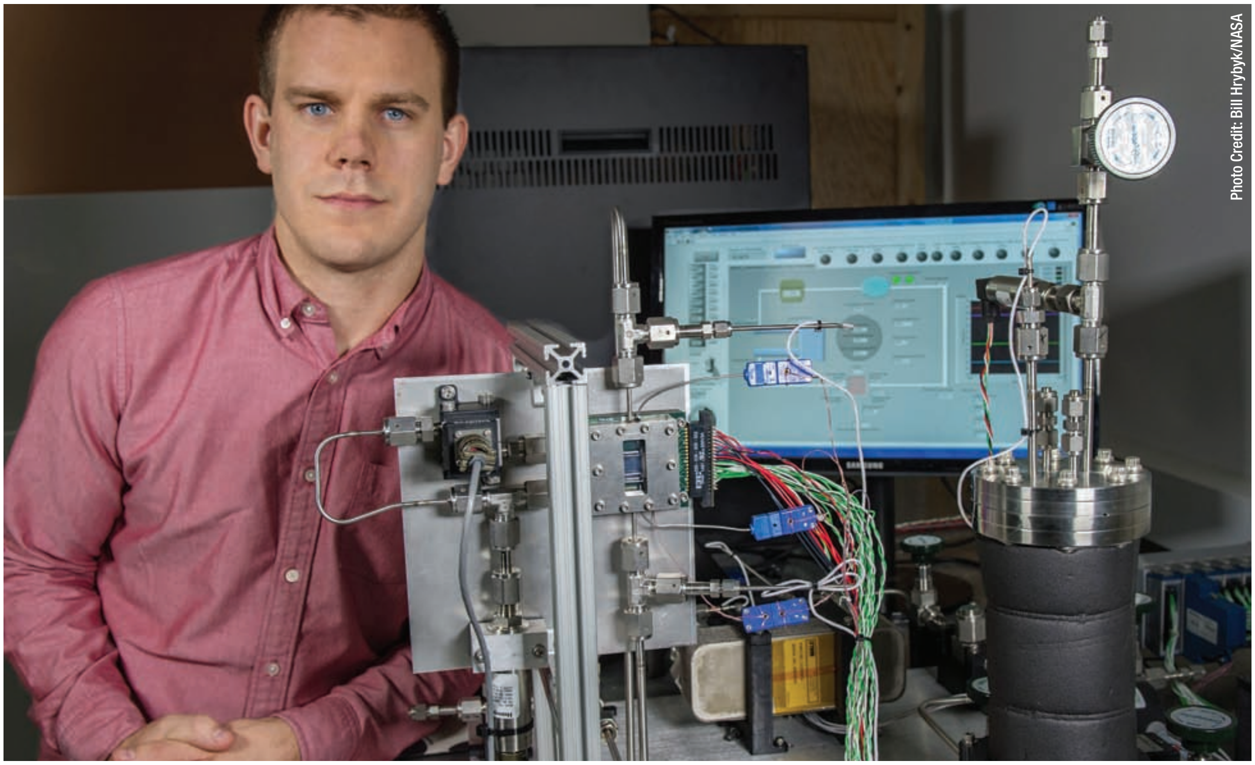


Photo Credit: Bill Hrybyk/NASA

Technologist Franklin Robinson poses with a testbed he's developed to experiment with a new cooling technique for emerging 3-D integrated circuits.

Future integrated circuitry is expected to look a lot like skyscrapers: units will be stacked atop one another and interconnects will link each level to its adjacent neighbors, much like how elevators connect one floor to the next. The problem is how do integrated-circuit designers remove heat from these tightly packed 3-D chips? The smaller the space between the chips, the harder it is to remove the heat.

Although circuit designers are still working the challenge for commercial applications, the problem poses an especially difficult conundrum for those designing 3-D integrated circuitry for space-based uses. Due to the unique space environment, removing heat from power-dense electronics always has presented challenges, sometimes leading to inefficient designs, said Franklin Robinson, a Goddard thermal engineer, who is studying different cooling techniques so that NASA might benefit from this emerging technology in the future.

"These 3-D stacked integrated circuits are coming; they will be commercialized. We need to get ahead of the curve when they do become available," he said.

He's not alone in his enthusiasm for the newfangled technology. The thirst for more features and computing power has driven the electronics industry to adopt 3-D integrated-circuit technology. Though manufacturing and technical challenges remain, the emerging technology promises to save space in future electronic devices and instruments — chips are stacked atop each other and not spread over a circuit board. With shorter wiring linking the chips, data would move both horizontally and vertically, improving bandwidth, computational speed, and performance, all while consuming less power.

Greater functionality in a smaller package is especially important to NASA, Robinson said. "Miniature instruments are vital to NASA's emerging mission portfolio. The goal for these instruments is to provide the greatest functionality in a small package."

To make sure NASA benefits from this emerging 3-D circuit technology, Robinson and his team have begun investigating a technology that would remove heat by flowing a coolant through embedded channels about the size of a human hair within or between the chips.

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cuttingedge • goddard's emerging technologies

# Brave New World

*Heliophysics Division Continues Leadership in CubeSat Missions*

Goddard's Heliophysics Division — an early adapter of the increasingly more capable CubeSat platform often no larger than a regulation soccer ball — continues its leadership in the use of these tiny satellites to study space weather, which can adversely affect low-Earth-orbiting spacecraft.

Two missions, the recently selected CuSPP+ — short for CubeSat mission to study Solar Particles over the Poles Enhancement — and the National Science Foundation-funded ExoCube are two such examples.

## CuSPP+ and MERIT

CuSPP+, which NASA recently selected as one of its first interplanetary CubeSat missions (CuttingEdge, Summer 2015, Page 3), will serve as a proof-of-concept for using CubeSats as space weather stations. With its suite of three miniaturized instruments, including the Goddard-developed Miniaturized Electron and Proton Telescope, or MERiT, the mission will study the dynamic particles and magnetic fields coming from the sun. MERiT, in particular, will send back counts of the numbers of charged particles it encounters at different energy levels.

"This particle detector is much smaller than others with similar functions," said Eric Christian, lead Goddard scientist for CuSPP+. He credits his team's ability to reduce MERiT's size and power use to a specific type of circuit, called an application-specific integrated circuit, or ASIC. Under the direction of Goddard research scientist Nikolaos Paschalidis, the center is starting to curate a library of ASICs that are available to scientists designing new instruments.

"It takes some money to develop these ASICs, but once you have them on hand, they can go in quite a few instruments," Christian said.

The ASIC used in MERiT is a lightweight analog-to-digital converter that uses only a small amount of power compared to other similar circuits. This chip is essential for converting the small surge of electricity caused by a particle hitting the detector — the analog signal — to a number that the instrument's computer can read and store.

In addition to Goddard's particle detector, CuSPP+ also will carry an instrument to measure magnetic fields, called a magnetometer, made by NASA's Jet Propulsion Laboratory and an energetic particle detector from the Southwest Research Institute in San Antonio, Texas.

## Goddard-Built Instrument Provides Big Payback

Another Goddard-developed CubeSat instrument, the Mini Ion-Neutral Mass Spectrometer, or Mini-INMS — the smallest of its kind measuring just 3.5 X 3.5 inches square and 5 inches tall — recently returned its first data analyzing the composition of

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*This is an artist's rendering of CuSSP+, among NASA's first interplanetary CubeSat missions.*

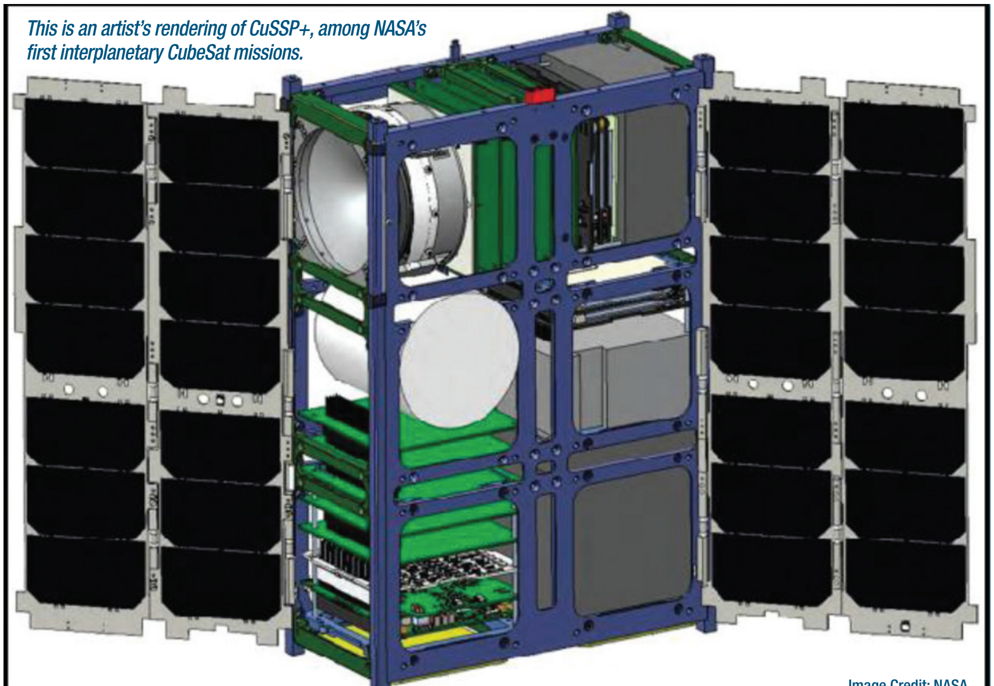
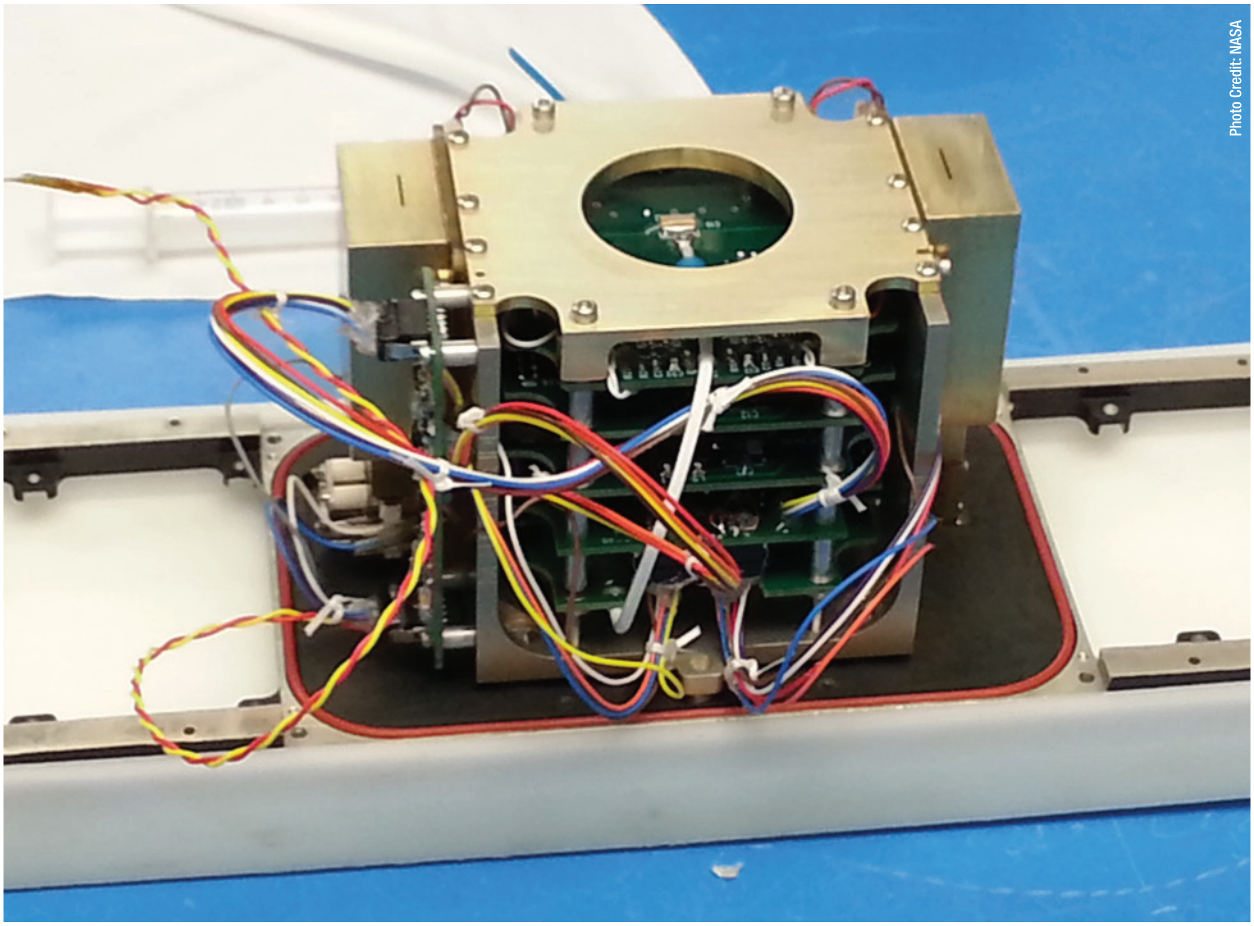


Image Credit: NASA




*The smallest space weather spectrometer ever built: Launched onboard the ExoCube CubeSat in January 2015, the Mini Ion-Neutral Mass Spectrometer, or Mini-INMS, has provided some of the first direct measurements of particles in the upper atmosphere since the 1980s.*

Earth's dynamic neighborhood, demonstrating it to be a technology ready for use on future missions.

The Mini-INMS was launched earlier this year aboard a National Science Foundation-funded mission called ExoCube (*CuttingEdge*, Spring 2014, Page 8). It measures the densities of a variety of particles in the upper reaches of Earth's atmosphere, observing how these densities change in response to daily and seasonal cycles.

These measurements include the first hydrogen measurements ever directly measured in the region by a mass spectrometer, and the first direct oxygen, helium, and nitrogen measurements since the early 1980s. Hydrogen is of particular interest, as its presence can contribute substantially to the total electron population around Earth, which, in turn, is a crucial parameter in understanding and modeling the space environment and its effects on satellites.

"It was a real challenge because there's never been an instrument like this made this small," said Paschalidis, science lead for the Mini-INMS instrument at Goddard. "But we had a great team and we put it together in just one year."

## Like a Bulldozer

The Mini-INMS instrument is built with an opening to face the direction in which the satellite flies. Like a bulldozer scooping up dirt as it moves, this open mouth naturally catches particles as the satellite speeds along at almost 5 miles per second.

Once inside the instrument, the particles are accelerated to about the same energy. Pulses of these energetically homogenous particles are allowed to zoom through two gated systems, one to measure ions and one for the neutrals, which must be converted to ions before they enter the main instrument. The lighter they are, the faster they'll go. Hydrogen will cross first, then helium, nitrogen, and finally oxygen. By counting each set at the

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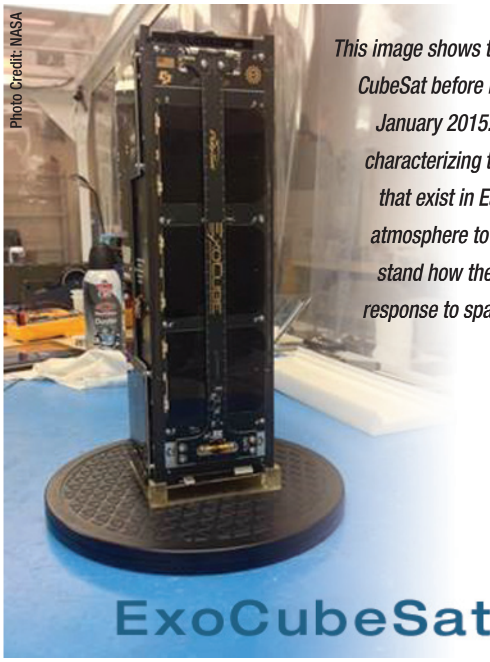
## New World, *continued from page 19*




*This image shows the ExoCube CubeSat before its launch in January 2015. ExoCube is characterizing the particles that exist in Earth's upper atmosphere to help understand how they change in response to space weather.*

final detector, researchers can easily calculate how many of each type is present.

"We've found that this first version of the instrument has adequate sensitivity to separate hydrogen, helium, nitrogen, and oxygen particles. We're seeing a good read of all the space particles," said Paschalidis. "It's even sensitive enough to detect a bit of carbon from a fingerprint left on the side of the CubeSat from when it was being built."

Proof of the Mini-INMS capabilities also opens doors for a host of other flight possibilities. An improved version is already being incorporated into a new heliophysics CubeSat being built at NASA Goddard called Dellingr, a name derived from the god of the dawn in Norse mythology (*CuttingEdge*, Fall 2014, Page 4). Paschalidis also is exploring sending a version into orbit around the moon.❖

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## Stacked, *continued from page 17*

In contrast, removing heat in more traditional 2-D integrated circuits is significantly different, he explained. Designers create a "floor plan," keeping the heat-generating devices 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 box-mounted radiator.

"This approach is not applicable to chip stacks because one or more of the chips in the stack is not in contact with the printed circuit board," he said. "However, we can remove the heat by flowing a coolant through these tiny, embedded channels."

To further improve the microchannel coolers, the team also is investigating the effectiveness of "flow boiling," where, as its name implies, the coolant would boil 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. It also relies on the working fluid's latent heat of vaporization, which reduces the flow rate, minimizing pumping power.

Another potential benefit exists: flow boiling in miniature channels could be insensitive to gravity, which is important when designing a technology that ultimately must fly in a low-gravity environment, he said.

Under his research, Robinson is evaluating two-phase flows in miniature channels, with the goal of producing a list of criteria for channel dimensions, flow parameters, and fluid properties that produce gravity insensitivity.

"This is essential because some systems experience variations in performance with changes in gravity," he said. "This is troublesome because on-orbit performance may not match terrestrial performance. By mapping the conditions that provide gravity insensitivity, we can dramatically reduce the risk for space-based applications." ❖

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Cutting edge Goddard's Emerging Technologies

*CuttingEdge* is published quarterly by the Office of the Chief Technologist at the Goddard Space Flight Center in Greenbelt, Md. Formerly known as *Goddard Tech Trends*, the publication describes the emerging, potentially transformative technologies that Goddard is pursuing to help NASA achieve its mission. For more information about Goddard technology, visit the website listed below or contact Chief Technologist Peter Hughes, *Peter.M.Hughes@nasa.gov*. If you wish to be placed on the publication's distribution list, contact Editor Lori Keesey, *Lori.J.Keesey@nasa.gov.* NP-2015-9-354-GSFC