National Aeronautics and Space Administration

Cutting edge

Goddard's Emerging Technologies

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Laser on a Chip:

NASA Embraces Integrated Photonics

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Goddard Tapped to Build NASA's First Integrated-Photonics Modem

A Goddard team has been tapped to build a new type of communications modem that will employ an emerging, potentially revolutionary technology that could transform everything from telecommunications, medical imaging, and advanced manufacturing to national defense.

In October 2016, a Goddard team will begin developing NASA's first integrated-photonics modem, a cell phone-size device whose optics-based functions, including lasers, switches, and wires, will be incorporated literally onto a microchip — much like an integrated circuit found in all electronics hardware.

The so-called Integrated LCRD LEO (Low-Earth Orbit) User Modem and Amplifier (ILLUMA) will be installed on the International Space Station in 2020 where it will serve as a low-Earth terminal for NASA's multi-year Laser Communications Relay Demonstration (LCRD) mission, demonstrating yet another capability for high-speed, laser-based communications.

Data Rates Demand New Technology

Since its inception in 1958, NASA has relied exclusively on radio frequency (RF)-based communications. Today, with missions demanding higher data rates than ever before, the need for LCRD has become more critical, said Don Cornwell, director of NASA's Advanced Communications and Navigation Division, which is funding the modem's development.

LCRD promises to transform the way NASA sends and receives data, video, and other information. It will use lasers to encode and transmit data at rates 10 to 100 times faster than today's RF radios, using significantly less mass and power.

Such a leap in technology could deliver video and high-resolution spacecraft measurements from across the solar system — permitting researchers to make detailed studies of conditions on

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About the Cover

In this photo, Goddard laser expert Mike Krainak is shown with a portion of the spaceflight modem flying on NASA's Laser Communications Relay Demonstration mission. Krainak and his team plan to replace portions of this fiber-optic receiver with an integrated-photonics circuit, whose size will be similar to the chip he is holding, and test the advanced modem aboard the International Space Station.

Photo Credit: Bill Hrybyk/NASA

other worlds much like how scientists today track hurricanes and other climate and environmental changes here on Earth.

The project, which is expected to begin operations in 2019, isn't NASA's first foray into laser communications. A payload aboard the Lunar Atmosphere and Dust Environment Explorer demonstrated record-breaking download and upload speeds to and from lunar orbit at 622 megabits per second (Mbps) and 20 Mbps, respectively, in 2013.

LCRD, however, is a fully operational system, not just an experiment. It involves a hosted payload and two ground stations capable of relaying data at more than a gigabit per second.

The mission will dedicate the first two years to demonstrating a fully operational system, from geosynchronous orbit to ground terminals. Once NASA demonstrates that capability, it plans to use ILLUMA to test communications between geosynchronous and low-Earth-orbit spacecraft, Cornwell said.

Not an Ordinary Terminal

ILLUMA, however, won't be an ordinary terminal. It incorporates an emerging technology — integrated photonics — that is expected to transform any technology that employs light. This includes everything from Internet communications over fiber-optic cable to spectrometers, chemical detectors, and surveillance systems, to name just a few.

"Integrated photonics are like an integrated circuit, except they use light rather than electrons to perform a wide variety of optical functions," Cornwell said. Recent developments in nanostructures, meta-materials, and silicon technologies have expanded the range of applications for these highly integrated optical chips. Furthermore, they could be lithographically printed in mass — just like electronic circuitry today — further driving down the costs of photonic devices.

"This technology will enable all types of NASA missions, not just optical communications on LCRD," Cornwell added.

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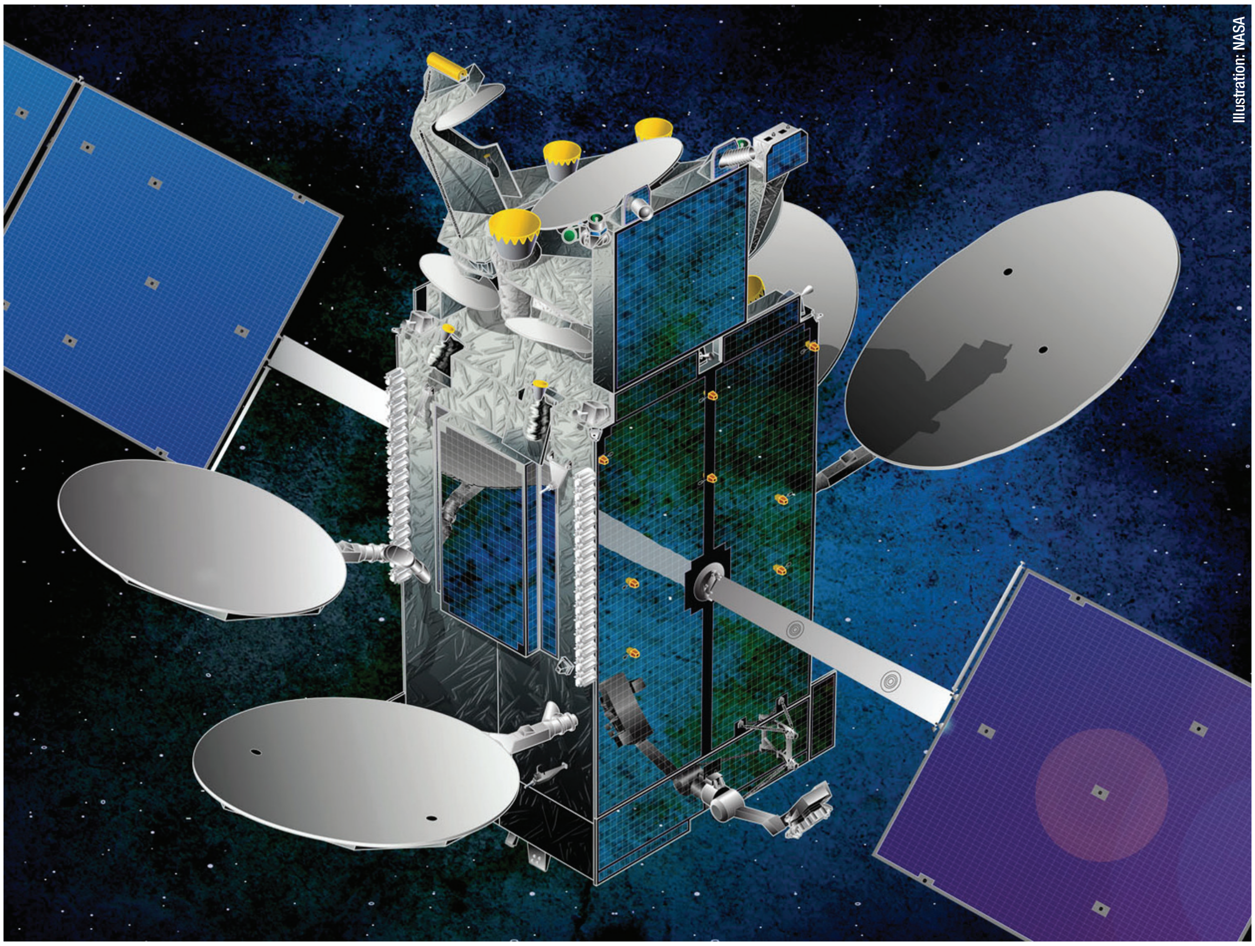

NASA's Laser Communications Relay Demonstration mission, shown here, will test a modem that will employ an emerging technology called integrated photonics.

"We've pushed this for a long time," said Mike Krainak, who is leading the modem's development at Goddard. "The technology will simplify optical-system design. It will reduce the size and power consumption of optical devices, and improve reliability, all while enabling new functions from a lower-cost system. It is clear that our strategy to leverage integrated-photonic circuitry will lead to a revolution in Earth and planetary-space communications as well as in science instruments."

In addition to leading ILLUMA's development, Krainak serves as NASA's representative on the country's first consortium to advance integrated photonics. Funded by the Department of Defense, the non-profit American Institute for Manufacturing Integrated Photonics, with headquarters in Rochester, New York, brings together the nation's leading technological talent to establish global leadership in integrated photonics. Its primary goal is developing low-cost, high-volume, manufacturing methods to merge electronic integrated circuits with integrated-photonic devices.

NASA's Space Technology Mission Directorate also appointed Krainak as the integrated-photonics lead for its Space Technology Research Grants Program, which supports early-stage innovations. The program recently announced a number of research awards under this technology area (see related story below).

First Step in Demonstrating Photonics

Under the ILLUMA project, Krainak and his team will reduce the size of the terminal, now about the size of two toaster ovens — a challenge made easier because all light-related functions will be squeezed onto a microchip. Although the modem is expected to use some optic fiber, ILLUMA is the first step in building and demonstrating an integrated-photonics circuit that ultimately will embed these functions onto a chip, he said.

ILLUMA not only will flight qualify the technology, but also demonstrate a key capability for future spacecraft. In addition to communicating to ground stations, future satellites will require the ability to communicate with one another, he said.

"What we want to do is provide a faster exchange of data to the scientific community. Modems have to be inexpensive. They have to be small. We also

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NASA Selects Five Integrated-Photonics Research Projects

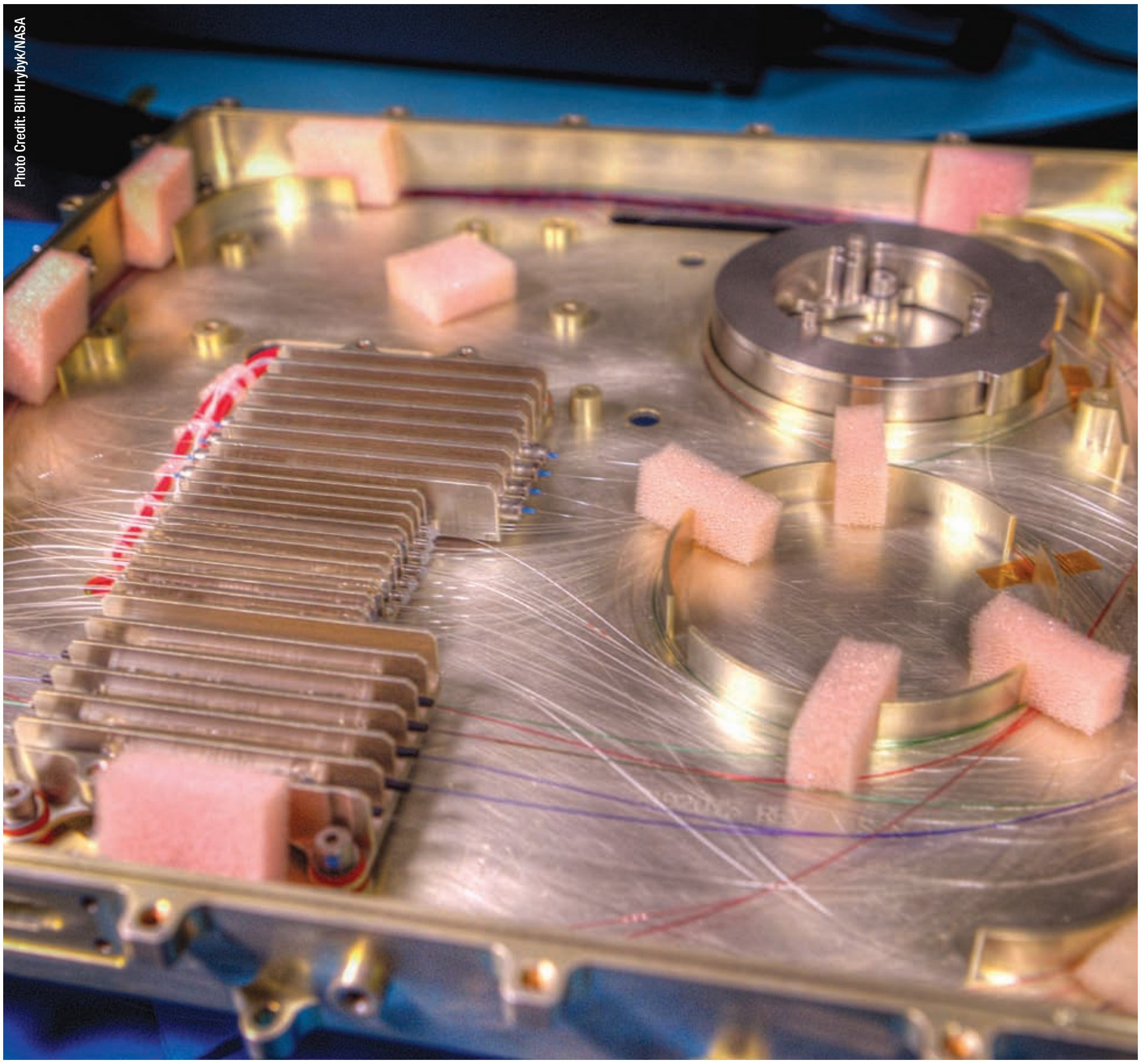
NASA's Space Technology Mission Directorate (STMD) chose five university-led teams to further study different applications of an emerging, potentially revolutionary technology called integrated photonics.

Under STMD's Early Stage Innovations awards, recipients will receive as much as a half-million dollars over two to three years to advance technologies tackling high-priority needs. Of the 15 proposals selected, five address integrated photonics, an emerging technology expected to transform any technology that employs light to carry out a specific job. This includes everything from Internet communications over fiber-optic cable to spectrometers, chemical detectors, and surveillance systems, to name just a few (see related story, page 2).

"This is superb recognition by NASA of the importance of integrated photonics," said Mike Krainak, a Goddard laser engineer who serves as NASA's representative on a recently formed non-profit consortium aimed at further advancing the technology.

NASA selected the following researchers and topics:

- **Karen Bergman,** Columbia University, Ultra-Low Power CMOS-Compatible Integrated-Photonic Platform for Terabit-Scale Communications
- **Seng-Tiong Ho,** Northwestern University, Compact Robust Integrated PPM Laser Transceiver Chip Set with High Sensitivity, Efficiency, and Reconfigurability
- **Jonathan Klamkin,** University of California-Santa Barbara, PICULS: Photonic Integrated Circuits for Ultra-Low size, Weight, and Power
- **Paul Leisher,** Rose-Hulman Institute of Technology, Integrated Tapered Active Modulators for High-Efficiency Gbps PPM Laser Transmitter PICs
- **Shayan Mookherjea,** University of California-San Diego, Integrated Photonics for Adaptive Discrete Multi-Carrier Space-Based Optical Communication and Ranging



This is a portion of the spaceflight modem flying on NASA's Laser Communications Relay Demonstration. A Goddard team plans to replicate this fiber-optic receiver, replacing portions of it with an integrated-photonics circuit. The team then plans to test the device on the International Space Station.

have to keep their weight down," Krainak said. The goal is to develop and demonstrate the technology and then make it available to industry and other government agencies, creating an economy of scale that will further drive down costs. "This is the pay off," he said.

Although integrated photonics promises to revolutionize space-based science and interplanetary communications, its impact on terrestrial uses also is equally profound, Krainak added. One such use is with data centers. These costly, very large facilities house servers that are connected by fiber-optic cable to store, manage, and distribute data. Integrated photonics promises to dramatically reduce the need for and size of these behemoths — particularly since the optical hardware needed to operate these facilities will be printed onto a chip. In addition to driving down costs, the technology promises faster computing power.

"Google, Facebook, they're all starting to look at this technology," Krainak said. "As integrated photonics progresses to be more cost effective than fiber optics, it will be used," Krainak said. "Everything is headed this way." ❖

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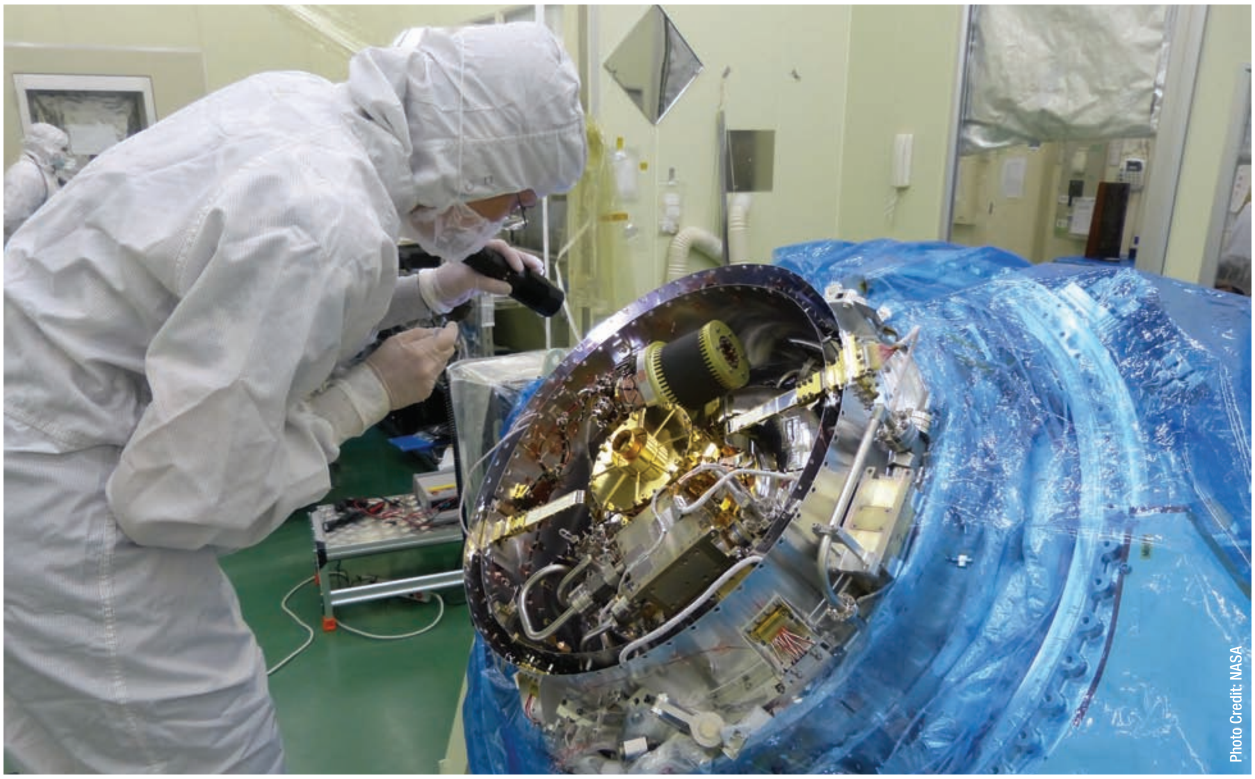
Astro-H Set to Launch in February

Japanese Mission Carries Advanced Goddard-Developed Instrument



An instrument scientist inspects the Soft X-ray Spectrometer before its final closing. The instrument is one of four that will fly on the Japanese-led Astro-H mission launching in February.

A devastating 9.0-magnitude earthquake and tsunami in 2011 may have delayed the construction of Japan's Astro-H mission, but ultimately it didn't sideline the observatory that will carry an advanced Goddard-developed instrument designed to study the high-energy universe.

Officials with the Japan Aerospace Exploration Agency (JAXA) now are set to launch the mission on February 12 from the Tanegashima Space Center aboard an H-IIA rocket. The observatory, with its suite of four instrument payloads, will continue the science started by JAXA's Suzaku mission that officially ended in September 2015.

No one will be happier than Goddard scientist Richard Kelley.

Microcalorimetry Enables Breakthrough Investigations

He and his team built the observatory's more capable Soft X-ray Spectrometer (SXS), which will perform a wide variety of breakthrough investigations — namely, studying the motion of matter approaching the event horizons of black holes, the abundances of elements, and the evolution of galaxies and galaxy clusters. Astro-H carries three other instruments: the Soft X-Ray Imager, the Hard X-Ray Imager, and the Soft Gamma-ray Detector.

While similar in many respects to the Goddard-built X-ray Spectrometer that flew on Suzaku, SXS offers a number of significant improvements in the area of detector performance, cooling technologies, and collecting area — advancements made possible by Goddard's initial investment in these technologies, said Kelley. He was named Goddard's Innovator of the Year in 2008 because of his work advancing SXS-related technologies, including a detection technique called microcalorimetry (*Goddard Tech Trends*, Fall 2008, Page 2).

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 physical properties of the object emitting the radiation. To measure as many X-ray photons as possible, Kelley

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and his team placed an array of microcalorimeter detectors at the focus of a large X-ray telescope. The detector package and cooling system then were placed inside a dewar.

SXS Microcalorimeter Array

Chief among the instrument's improvements is the instrument's 36-pixel microcalorimeter array. Actually larger in size than the 32-pixel array that flew on Suzaku, it offers better energy resolution because the team used improved absorbers, which help convert the individual X-rays into heat, and operated it at an even lower temperature, Kelley said.

While the Astro-H instrument represents a jump in capability, technology marches on, he added. Since SXS's selection in 2008, his team has advanced the technology and is now developing a 4,000-pixel microcalorimeter array for the European-led Advanced Telescope for High-ENergy Astrophysics mission, expected to launch late next decade.

"The technology has increased dramatically," Kelley said. "In 2008, we couldn't have proposed such an array because its technology-readiness level just wasn't high enough."

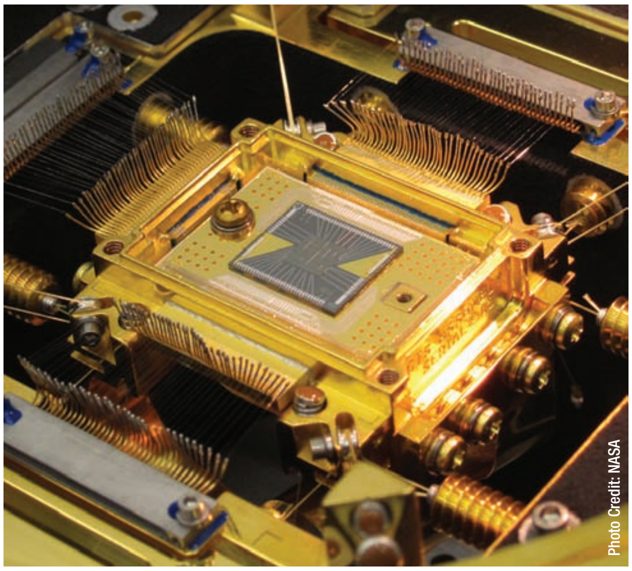
Onboard Refrigerator

Just as important as SXS's 36 microcalorimeters, however, is its cooling technology. When NASA selected Kelley and his team to build the Astro-H instrument, it baselined a two-stage adiabatic demagnetization refrigerator (ADR), a mechanical cooling system that operates much like a household refrigerator using liquid helium as its coolant.

However, NASA wanted to make sure the dewar remained at a super-cold temperature even if the cooling system ran out of coolant — a requirement that came about due to the unforeseen coolant boil-off that occurred on Suzaku, rendering the X-ray spectrometer unusable 30 days after the observatory's deployment, Kelley said. Consequently, the team added a third stage to the cooling system.

In addition to being more efficient, the three-stage ADR runs longer before needing a recharge. But better yet, the never-before-flown three-stage ADR will cool the dewar with or without the system's liquid helium coolant.

"On Suzaku, once the coolant was gone, so was the instrument," Kelley said. "NASA wanted to push beyond that and provide more capability. In other



This image shows the Soft X-ray Spectrometer's 36-pixel microcalorimeter array flying on the Astro-H mission launching in February.

words, redundancy was the driving requirement for flying the three-stage ADR."

X-ray Filters and Mirror Segments

Kelley said SXS also is equipped with stronger X-ray filters situated in front of an aperture intricately built into the dewar. The aperture allows X-rays to enter the dewar. Should ice build up on the filters, mission operators can defrost them, much like how drivers can eliminate frost and ice on vehicle windows.

The instrument's mirror assembly also benefited from past R&D funding. The assembly is so good, in fact, that Kelley's team produced two: one for SXS and another for Astro-H's Soft X-ray Imager, built by JAXA.

Consisting of 1,624 curved mirror segments all nested inside a canister, the assembly is lightweight and relatively inexpensive. The Goddard team made the mirror segments from commercial aluminum and then coated each with a special epoxy and a thin gold film to assure that each was smooth enough to efficiently reflect X-rays onto the microcalorimeter array.

"Our technological innovation is a higher-spectral resolution instrument, with higher collecting area — all built with a relatively small team working very closely with a team of scientists and engineers in Japan," Kelley said. ❖

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SPECIAL REPORT: Year of the CubeSat

Gaining faster, less-expensive access to space has become the clarion call for NASA and other organizations. An increasingly popular option is deploying smaller spacecraft that are less expensive to build and deploy. Although Goddard has invested in small-satellite technology for at least a decade, 2015 was particularly noteworthy and it appears that 2016 will be likewise. In this special report, CuttingEdge showcases a handful of upcoming or future CubeSat missions supported at least in part by Goddard R&D funding.

NASA Engineer Awaits Launch of CubeSat Mission Demonstrating Virtual-Telescope Technologies

Goddard engineers Neerav Shah and Phil Calhoun will realize a long-held ambition later this year when a SpaceX launch vehicle deploys two tiny satellites that will fly in a precise formation to create, in effect, a single or "virtual" telescope benefitting a range of scientific disciplines.

Through a NASA international agreement, Shah and his team have partnered with South Korea's Yonsei University and the Korea Aerospace Research Institute (KARI) to validate technologies that would allow a pair of miniature spacecraft to fly in tandem along an inertial line of sight toward the sun and then hold that configuration — a feat not yet performed in space.

Photo Credit: Debbie McCallum/NASA

A team of Goddard engineers assisted in the development of the micro-Cathode Arc Thruster system, which will maintain CANYVAL-X's alignment to an inertial target. They are pictured here with the technology. Members include: (front center): Matt Clovin; (left to right): Bob Spagnuolo, Joe Roman, Phil Calhoun, Behnam Azimi, Mike Mahon, and Neerav Shah.

Called CANYVAL-X, short for the CubeSat Astronomy by NASA and Yonsei using Virtual Telescope Alignment eXperiment, the technology-demonstration mission is expected to launch in mid-2016 aboard a SpaceX Falcon launch vehicle.

Never-Before-Tried Demonstration

"The key differentiator with our mission is that we are attempting to align two satellites along an inertial line of sight to a distant celestial target and hold them in alignment for a long enough time to make a scientific measurement," said Shah. "Although others have flown two or more satellites in tandem, we are the first in the world to even try holding them in alignment to a distant source."

Currently, the European Space Agency (ESA) is developing Proba-3, a large-scale science experiment that will fly a pair of satellites in a tight formation to form a 492-foot-long solar coronagraph to study the sun's faint corona, its outer atmosphere. According to ESA, however, the mission isn't expected to launch until the end of 2018.

Virtual Telescope Beneficiaries

The technology's obvious beneficiaries in the future are scientists who study the sun's corona, and, more particularly, coronal mass ejections that hurl enormous bubbles of superheated gas across the solar system. Traveling at a million miles per hour, they can disrupt low-Earth-orbiting satellites and terrestrial power grids when they strike Earth. The technology also could be used by scientists searching for planets beyond the solar system.

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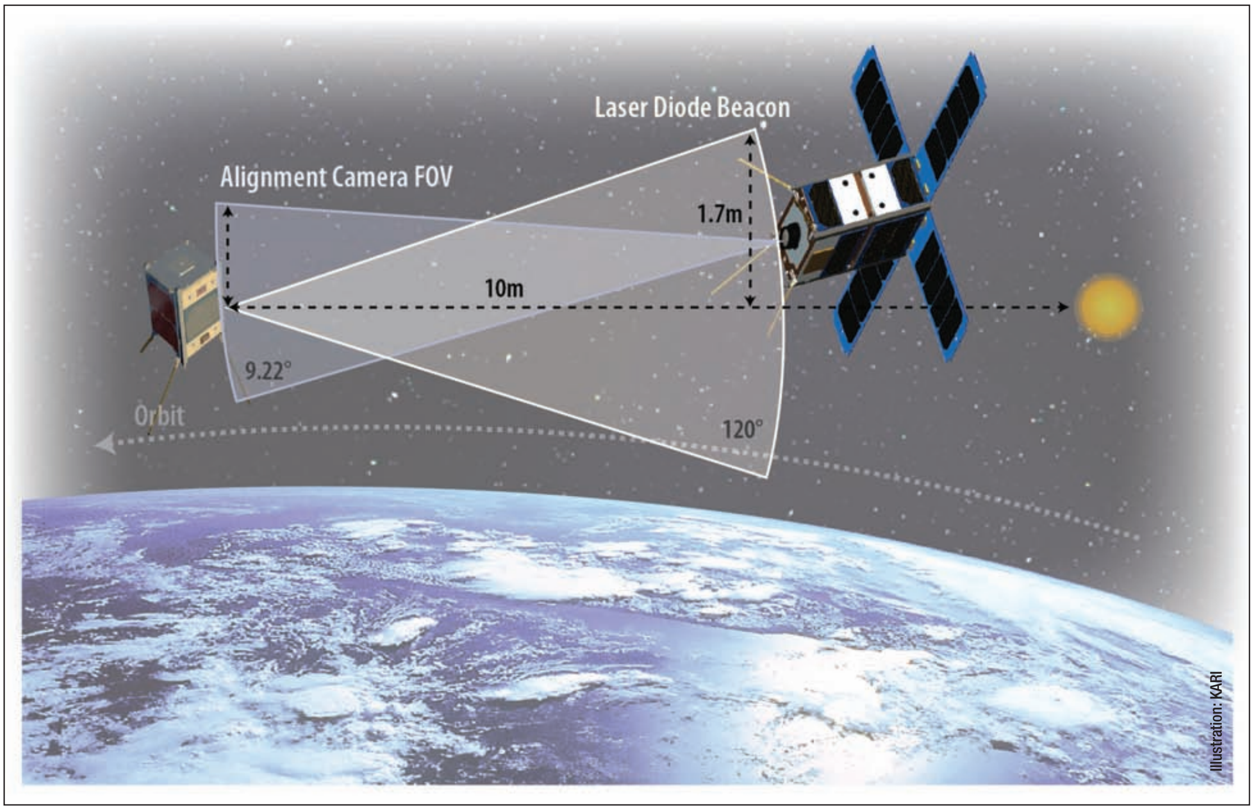

This artist's rendition shows how CANYVAL-X's two CubeSats will align once they are in orbit.

Both scientific disciplines rely on coronagraphs, which employ an occulter mask to block bright starlight to reveal faint objects hidden by the star's bright light and a camera or spectrograph to gather measurements. Today, space-based coronagraphs house both the occulter and a camera or spectrograph in the same telescope, positioning them relatively close to one another.

> *"Although others have flown two or more satellites in tandem, we are the first in the world to even try holding them in alignment to a distant source."*
> ***— Engineer Neerav Shah***

Some scientists believe, however, that they could gather even more detailed information if they positioned the occulter hundreds of feet away from the camera or spectrograph. A case in point is the moon, itself. When aligned with the sun — called an eclipse — the moon provides a near-perfect coronagraph. "Creating a single telescope that achieves these distances is not possible. It would be too large to launch into space," Shah said.

A solution is launching two spacecraft — one that carries the occulter disk, the other the science instrument. Flying these devices on two separate spacecraft that are precisely aligned to the target of interest solves this challenge, he added. "Formation flying offers the ability to increase the separation distances, which leads to reduced diffracted light."

"Actually any mission where you need to fly in tandem to gather a measurement, would certainly benefit," Shah said. "If we demonstrate the concept, we will enable the next generation of space telescopes."

CANYVAL-X Demonstration

Under the CANYVAL-X technology demonstration, the team plans to position a 2U and a 1U CubeSat in a 435-mile sun-synchronous orbit, where the two will maintain a tight alignment along a line of sight to the sun.

The larger of the two spacecraft will carry two Goddard-provided technologies that make up the mission's all-important guidance, navigation and control (GN&C) system: a miniature sun sensor and the micro-Cathode Arc Thruster (mCAT) system.

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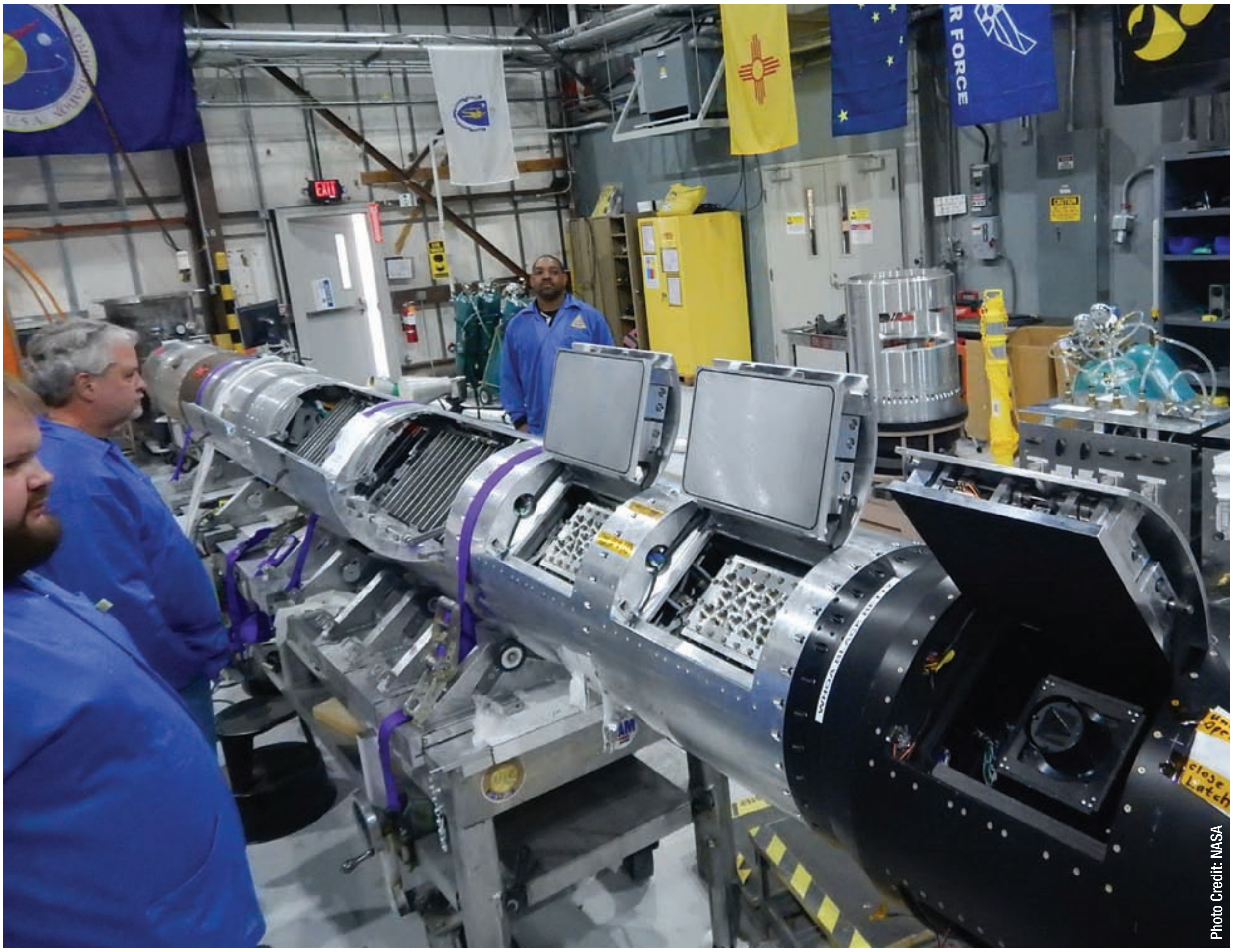
SPECIAL REPORT

A Gift That Keeps Giving

NASA's First Wide-Field Soft-X-ray Camera Miniaturized; Selected for CubeSat Mission



The CuPID/WASP payload (front of rocket) was integrated into a Black Brant IX sounding rocket and launched in early December 2015. The instrument returned valuable data needed by three different scientific disciplines.

NASA's first wide-field soft X-ray camera, which incorporated a never-before-flown focusing technology, is a gift that keeps giving.

NASA recently selected a miniaturized version of the original instrument to fly as a 3U CubeSat to study "charge exchange," a phenomenon that occurs when the 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 gas in interplanetary space.

The selection by NASA's Heliophysics Technology and Instrument Development for Science (H-TIDeS) program follows a successful demonstration of the instrument, which flew aboard a Black Brant IX sounding rocket in December 2015.

It was one of five experiments on the Diffuse X-ray emission from the Local galaxy-2 mission, funded by NASA's Astrophysics Division, and developed jointly by the Goddard team and University of Miami professor Massimiliano Galeazzi.

The bread loaf-size CubeSat instrument, which goes by two names — WASP (Wide Angle Soft x-ray Planetary camera) and CuPID (Cusp Plasma Imaging Detector), depending on whom is using the data — is the latest incarnation of the Sheath Transport Observer for the Redistribution of Mass (STORM) instrument.

Three years ago, a team of three Goddard scientists demonstrated STORM aboard a Black Brant IX sounding rocket to prove that their concept for

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studying charge exchange would work (*CuttingEdge*, Winter 2013, Page 2). The charge-exchange process happens when 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.

So valuable was the resulting data that the three decided to miniaturize STORM and compete for a CubeSat flight opportunity. Now about half the size of STORM, the instrument will be further refined under the H-TIDeS funding, ultimately carrying its own avionics system.

"Actually, it was quite a coup," said Instrument Principal Investigator Michael Collier, a planetary scientist who worked with heliophysicist David Sibeck and astrophysicist Scott Porter to develop all instrument versions. "This imager has applications across many different fields and platforms. We figured we could miniaturize it and put it on a 3U CubeSat and still get good science."

> *"We figured we could miniaturize it and put it on a 3U CubeSat and still get good science."*
>
> ***— Scientist Michael Collier***

Like its predecessor, CuPID/WASP employs a "lobster-eye" optic made up of 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.

Because the instrument is considerably smaller than STORM, its collecting area isn't quite as good. However, the data is just as valuable to scientists, Porter said.

Since the phenomenon's discovery in the mid-1990s, scientists have observed the emission of charge-exchange X-rays from planets, the moon, comets, interplanetary space, possible supernova remnants, and galactic halos.

Planetary scientists have observed the emissions from the outer atmospheres of Venus and Mars, leading some to question whether the charge-exchange phenomenon contributes to the atmo-

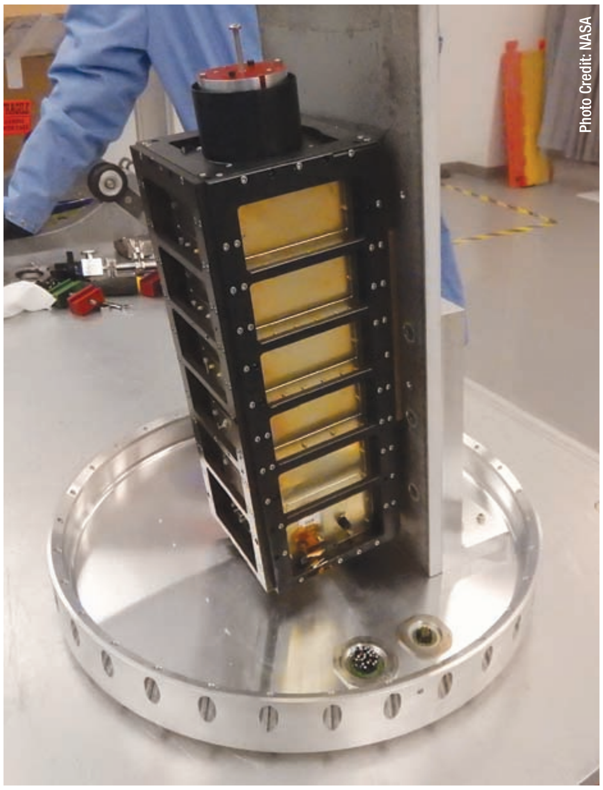
Photo Credit: NASA

The miniaturized CubeSat payload called both CuPID and WASP returned data about a physical phenomenon called charge exchange.

spheric loss on Mars. Heliophysicists also have observed soft X-rays from the outer boundaries of Earth's magnetosphere, the magnetic bubble that only partially shields Earth from hazardous solar storms. And astrophyscists have observed them, too — as unwanted noise in data collected by all X-ray observatories sensitive to soft X-rays.

As a result, planetary scientists and heliophysicists want to measure these emissions for scientific reasons, while astrophysicists want to remove them as noise.

Since the instrument's debut in 2012 and subsequent miniaturization as a CubeSat payload, a European-led team has begun considering developing a STORM-like instrument for its proposed Solar Wind Magnetosphere Ionosphere Link Explorer (*CuttingEdge*, Fall 2015, Page 8).

"Everyone is interested in getting this data, although for different reasons," Collier added. "These missions span three different disciplines, which is a rare occurrence in space science." ❖

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SPECIAL REPORT

Similar Mission Names, Different Objectives

Scientists Win Two CubeSat Opportunities

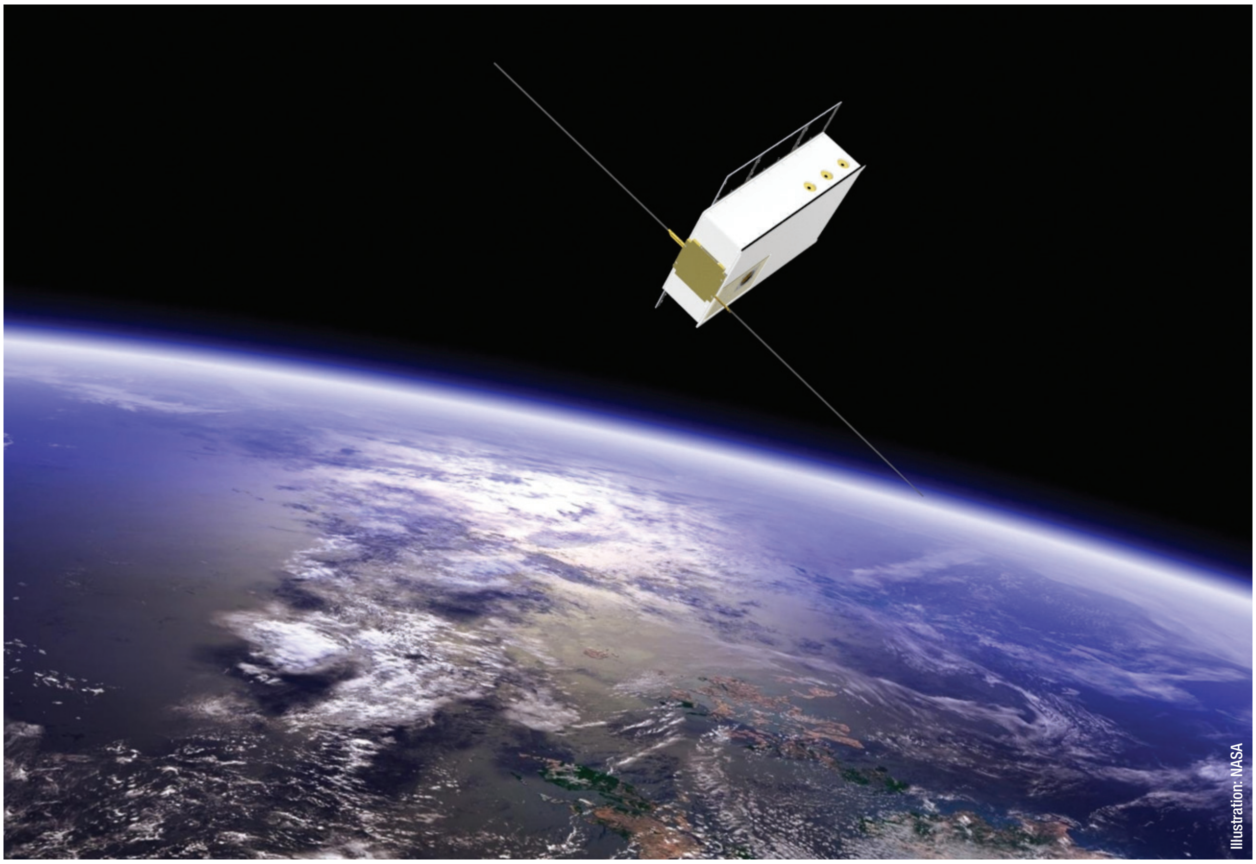

Illustration: NASA

This artist's rendition shows the design of the recently selected HaloSat mission.

Their names may be similar, but that's where the similarity ends.

A Goddard team has won funding to mature two instruments that would investigate the water cycle on the moon in a mission called HALO (Hydrogen Albedo Lunar Orbiter) and a university-led team involving Goddard scientists Keith Jahoda and Steve Snowden has been tapped to develop HaloSat, which represents Goddard's first involvement with an astrophysics-related CubeSat mission.

HALO

"We think that if we successfully mature these instruments over the next year, we'll be in a good position to win the next CubeSat opportunity," said John Keller, a member of the team that received funding to mature HALO's Electrostatic Ion Analyzer and Energetic Neutral Analyzer (ENA). ENA borrows heavily from a previously flown small-satellite mission called FASTSAT sponsored by the U.S. Air Force (CuttingEdge, Winter 2012, Page 10).

To fly on the proposed HALO 6U CubeSat, the team, led by Goddard scientist Michael Collier, must reduce the instruments' size by a factor of two, Keller said.

Although scientists know that the moon has more water than previously thought, they don't understand the role that solar wind and micrometeorite impacts play in its formation. To answer these questions, HALO, if eventually selected for development, would quantify the hydrogen budget on the moon to determine its effect on its water cycle.

HaloSat

Meanwhile, work has begun on HaloSat, led by University of Iowa professor Phil Kaaret. This relatively inexpensive 6U CubeSat mission is being built with commercially available detectors and other components. Once deployed in early 2018, it will conduct a near all-sky survey to address the cosmological missing baryon problem, Co-Investigator Jahoda said.

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SPECIAL REPORT

Combatting the Noise

CubeSat to Test RFI-Mitigation Technologies

It's getting noisier and noisier out there and now the cacophony of broadcast and other communications signals has begun to seriously interfere with important Earth science research.

A Goddard team is collaborating with Ohio State University and NASA's Jet Propulsion Laboratory (JPL) to build and launch a new CubeSat mission that will test next-generation techniques for detecting and discarding radio-frequency interference (RFI), which is caused by satellite TV, automatic door openers, and other communications technologies that operate at microwave frequencies.

Funded by NASA's In-Space Validation of Earth Science Technologies, the CubeSat Radiometer Radio Frequency Interference Technology Validation (CubeRRT) specifically will evaluate a specialized digital-based spectrometer equipped with sophisticated algorithms that can detect and mitigate the radio interference that spills over and ends up as noise in scientific data.

Goddard is charged with developing the instrument's front-end microwave electronics and overseeing the instrument's integration onto the spacecraft. JPL, meanwhile, is building the instrument's backend digital electronics. The Wallops Flight Facility is handling ground-system design and operations, while Ohio State is procuring the spacecraft bus from the Boulder, Colorado-based Blue Canyon Technologies.

'Noise' Affects Radiometry

This manmade "noise" has proven especially troublesome for space-based radiometers, which use a portion of the microwave spectrum to passively gather data about moisture, atmospheric water vapor, sea-surface temperatures, and surface winds, among other climate-related conditions. Although specific frequency bands have been set aside for Earth observation and radio astronomy, the spectrum for commercial use is becoming increasingly crowded, overrunning the science-reserved bands and accelerating demands that more spectrum be set aside for commercial uses.

"As these sources expand over larger areas and occupy additional spectrum, it will become increasingly difficult to perform radiometry without an RFI-mitigation capability," said Jeffrey Piepmeier, a Goddard engineer and CubeRRT team member.

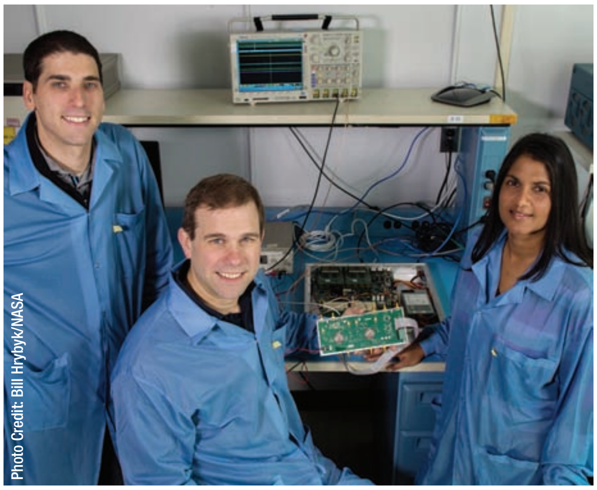

Photo Credit: Bill Hrybyk/NASA

Jared Lucey, Jeffrey Piepmeier, and Priscilla Mohammed, a research engineer at Morgan State University, are developing a new CubeSat mission to test RFI-mitigation strategies. They are shown here with a testbed for testing mitigation algorithms.

Picking Up Where SMAP Left Off

Expected to launch in 2018, the 6U CubeSat will pick up where other RFI-mitigation technology-development efforts have left off, Piepmeier added.

NASA's Soil Moisture Active Passive (SMAP) mission, for example, carries a state-of-the-art "smart" microwave radiometer equipped with one of the most sophisticated signal-processing systems ever developed by Goddard. SMAP, however, is tuned to a particular frequency band —1.4 GHz or "L-Band" — the wavelength ideal for detecting soil moisture.

With CubeRRT, however, the team plans to test techniques designed to mitigate RFI at higher frequencies — particularly in the 6 to 40 GHz range. These frequencies are ideal for passively gathering data about other conditions important to climate research.

"Successful mitigation not only will open the possibility of microwave radiometry in any RFI-intensive environment, but also will allow future systems to operate over a larger bandwidth, resulting in lower measurement noise," Piepmeier said. "This wasn't a problem 20 years ago, and it's just going to get worse." ❖

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Nikolaos Paschalidis Recognized as the 2015 IRAD Innovator of the Year

Nikolaos "Nick" Paschalidis doesn't want to tip his hand, but he can say with utmost certainty that NASA hasn't seen the last of him yet. He has big plans.

Goddard scientist Nikolaos Paschalidis shakes hands with Goddard Deputy Chief Technologist Deborah Amato after receiving his "IRAD Innovator of the Year" award at the Annual IRAD Poster Session late last year. Heliophysics Division Chief Michael Hesse looks on.

The heliophysicist, who received Goddard's 2015 "IRAD Innovator of the Year" award late last year, says he is focusing his energies now on developing new instruments, including compact instruments for distributed, multi small-satellite missions, and has identified several flight opportunities for his innovations. The future, he said, looks bright.

If history is any guide, Paschalidis is justified in his optimism. In 2015, Paschalidis enjoyed an exceptionally noteworthy year.

Five multi-purpose microchips, which he created 15 years ago to provide time-of-flight, energy, position, and other measurements, were put to the test in July 2015 when the New Horizons spacecraft reached Pluto. This accomplishment, however, was just the latest for his continually evolving technology.

These application-specific integrated circuits also flew on the Magnetospheric Multiscale mission, launched in March 2015, and previously, the Interstellar Boundary Explorer, Juno, MESSENGER, and the Van Allen Probes, among others. Upcoming missions, including Solar Orbiter and Solar Probe+, also will benefit from his past work and the new generation of microchips, Paschalidis said.

His Mini Ion-Neutral Mass Spectrometer (Mini-INMS) — the smallest instrument ever built of its type — returned valuable, much-sought-after data during the National Science Foundation-funded ExoCube mission that also launched in 2015 (*CuttingEdge*, Fall 2015, Page 18). "It took him just nine months from a sketch on a scrap of paper to develop a flight instrument," said Michael Hesse, Goddard's Heliophysics Division Chief. "That was amazing, unheard of in our field. While ExoCube is experiencing troubles, Nick's instrument works spectacularly."

Paschalidis, however, wasn't content flying INMS on just one CubeSat mission. He found another opportunity to fly an improved version of his instrument, earning a berth on the upcoming launch of a Goddard-developed 6U CubeSat called Dellingr (*CuttingEdge*, Fall 2014, Page 4).

In addition, his insights and microchip technology contributed to the award of two CubeSat missions: the Compact Radiation belt Explorer and, in 2015, the CubeSat Mission to Study Solar Particles over the Earth's Poles Enhancement (*CuttingEdge*, Fall 2015, Page 18). "These wins underscored his incalculable value to the center's efforts to position itself as a world-class developer of small-satellite missions, instrumentation, and components," said Goddard Chief Technologist Peter Hughes, whose organization selected Paschalidis for the award.

"Technically, I think Nick is as close to a genius as anyone can come. He is incredibly creative, finding solutions where others can't," Hesse added. "I'm really, really happy he got that award." ❖

A Mission of Firsts

ICESat-2 Carries Unique 3-D Manufactured Part

NASA's follow-on to the highly successful ICESat mission will employ a never-before-flown technique for determining the topography of ice sheets and the thickness of sea ice, but that won't be the only first for this long-anticipated mission.

Slated for launch in 2018, NASA's Ice, Cloud and land Elevation Satellite-2 (ICESat-2) also will carry a 3-D printed part made of polyetherketoneketone (PEKK), a material that has never been used in 3-D manufacturing, let alone flown in space.

"This is a first for this material," said Craig Auletti, lead production engineer on ICESat-2's only instrument, the Advanced Topographic Laser Altimeter System (ATLAS). The part is a bracket that supports the instrument's fiber-optic cables.

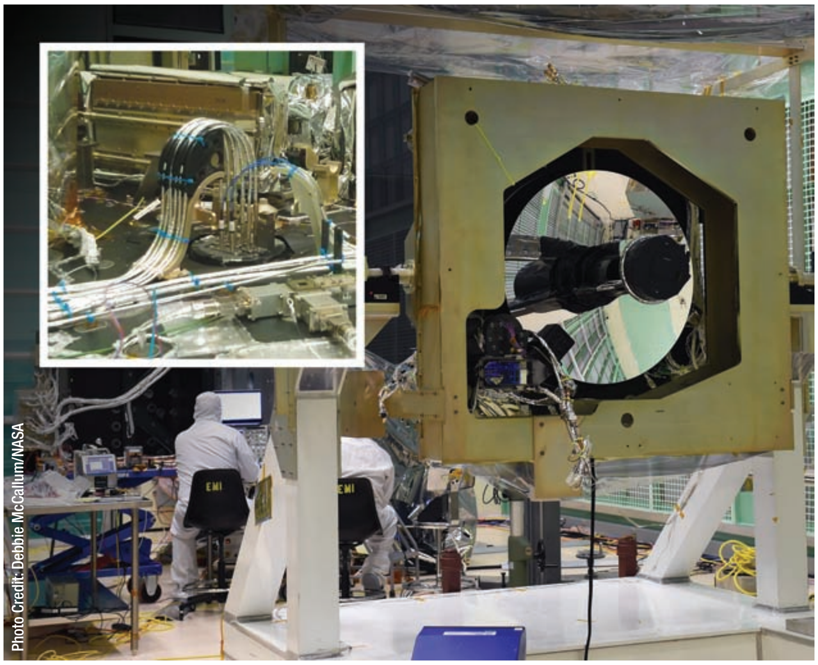

Photo Credit: Debbie McCallum/NASA

Main Photo: This image shows the ATLAS instrument inside a Goddard cleanroom where the instrument was assembled. Inset Photo: The 3-D manufactured part — a black bracket holding the instrument's fiber-optic cables — is visible in the back of the ATLAS instrument.

PEKK Offers Advantages

Instrument developers chose PEKK because it's strong, but perhaps more important, it's electrostatically dissipative — that is, it reduces the build up of static electricity to protect electrostatically sensitive devices. It also produces very little outgassing, a chemical process similar to what happens when plastics and other materials release gas, producing, for example, the "new car smell" in vehicles. In a vacuum or under heated conditions, these outgassed contaminants can condense on and harm optical devices and thermal radiators, significantly degrading instrument performance.

Although 3-D or additive manufacturing is used to create a variety of products, so far it remains a rare occurrence in spaceflight applications. In fact, the PEKK bracket is believed to be only the second 3-D manufactured part to be flown in a spaceflight instrument, said Oren Sheinman, the mechanical systems engineer on ATLAS.

Three-dimensional parts printed of Ultem 9085 were produced and flown on the International Space Station by the Ames Research Center's Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) program.

Additive or 3-D manufacturing is attractive because it offers a fast, low-cost alternative to traditional manufacturing. With additive manufacturing, a computer-operated device literally prints a solid object, layer by layer, using a high-power laser that melts and fuses powdered materials in precise locations using a 3-D CAD model. "Had we manufactured this part classically, it would have taken six to eight weeks. We got it in two days," Sheinman said, adding that costs to the project were up to four times less than with a traditionally machined part.

ATLAS: A Technical Marvel

The bracket, however is just one of the mission's firsts. ATLAS, itself, is a technical marvel, said ATLAS Instrument Scientist Tony Martino. It will be NASA's first space-borne, photon-counting laser altimeter and is expected to usher in a new, more precise method for measuring surface elevations.

As with its predecessor, ICESat-2 is designed to measure changes in ice-sheet elevations in Greenland and the Antarctic, sea-ice thicknesses, and global vegetation. However, it will execute its mission using a never-before-flown technique.

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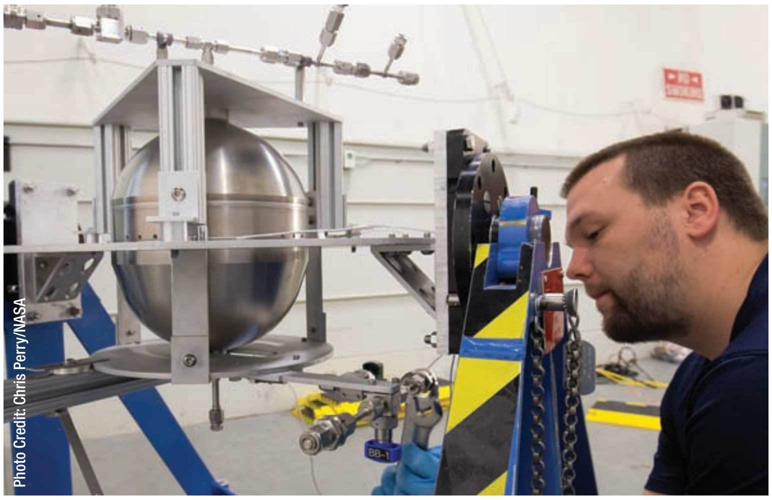
NASA Goes Green

Goddard Team Demonstrates Loading of Swedish Green Propellant

A Goddard team has successfully demonstrated the handling and loading of a new-fangled, Swedish-developed green propellant that smells like glass cleaner, looks like chardonnay, but has proven powerful enough to propel a satellite.

As part of an international agreement with the Swedish National Space Board (SNSB), the team simulated a flight-vehicle loading operation with LMP-103S Green Propellant at the Wallops Flight Facility. The team demonstrated the proper storage of the propellant and its loading into a flight-like tank provided by Moog Inc., an aerospace company interested in green-propulsion technology.



This image shows the tank that held the Swedish-developed green propellant. Kyle Bentley is pictured.

This was the first-ever demonstration of its type on a U.S. range, said Henry Mulkey, a Goddard engineer who led the effort.

The demonstration, which took place late in 2015, will be followed this year by two other tests. Goddard's Propulsion Branch is carrying out a fracture test to determine the behavior of a flight tank should it crack while loaded with the propellant. And at the end of 2016, the branch also plans to test-fire two Swedish-developed spacecraft thrusters powered by LMP-103S, said Caitlin Bacha, associate head of the Propulsion Branch.

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Mission of Firsts, *continued from page 15*

ICESat, which ended operations in 2009, employed a single laser, which made it more difficult to measure changes in the elevation of an ice sheet. With a single beam, researchers couldn't tell if the snowpack had melted or if the laser was slightly off and pointed down a hill. ICESat-2 overcomes those challenges by splitting the green-light laser into six beams, arranged in three pairs, firing continuously at a rapid 10,000 pulses per second toward Earth.

Unlike analog-laser altimetry, which uses analog detectors and digitizes the return signal, ICESat-2 will employ a technique called photon counting. Used in aircraft instruments, photon counting has not yet been used for altimetry in a spaceflight instrument. It more precisely records the time-of-flight of individual photons as they travel from the instrument, reflect off Earth's surface, and then are detected as they return to the instrument's detectors — measurements that scientists use to calculate Earth's surface elevation.

Perhaps more important to scientists who want to know how the ice sheets change over time, the multiple beams will give scientists dense cross-track samples that will help them determine a surface's slope, while the high-pulse rate will allow ATLAS to take measurements every 2.3 feet along the satellite's ground path — all at a higher resolution due to the photon counting.

"This is one of the new capabilities," Martino said. "We'll get cross track slope every time the satellite passes over." Furthermore, the satellite will pass over the same area every 90 days during ICESat-2's three-year mission, giving scientists a very detailed multi-year snapshot of how the ice is changing.

"It's almost completely built," Martino said, adding that the spacecraft will fly on the last Delta II launch vehicle. "All functional parts are there and our first comprehensive testing starts in February. We're on track." ❖

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All tests are designed to show that LMP-103S is a viable, higher-performing, safer, and less-expensive alternative to hydrazine, a highly toxic propellant that requires personnel to don cumbersome, full-body protective gear when handling and loading the propellant into spacecraft. By way of comparison, Mulkey said he mixed LMP-103S wearing just safety glasses and a smock.

Photo Credit: Chris Perry/NASA

A Goddard team, led by engineer Henry Mulkey (middle), prepares a tank containing a Swedish-developed green propellant before its simulated loading at the Wallops Flight Facility late last year. Kyle Bentley (squatting) and Joe Miller (standing to the right of Mulkey) assisted in the demonstration.

The propellant, which a Stockholm-based company, ECAPS AB, began developing about two decades ago with SNSB funding, is based on ammonium dinitramide, a high-energy salt. It made its debut about five years ago aboard PRISMA, a Swedish spacecraft equipped with two one-Newton thrusters. (A Newton is a unit of force.)

NASA's Pre-Aerosol, Clouds, and ocean Ecosystem mission, which the agency formally assigned to Goddard last year, also is investigating the use of LMP-103S-powered thrusters.

"We gained a lot of knowledge and hands-on experience from this pathfinder activity," Mulkey said. "We can take this experience and directly apply it to other flight-loading activities."

The Other Green Propellant

Goddard's experimentation with LMP-103S is just part of NASA's green-propellant story.

Goddard and a handful of other NASA centers also are participating in the Green Propellant Infusion Mission (GPIM). GPIM, which NASA's Space Technology Mission Directorate expects to launch in 2016, will carry 31 lbs. of another green propellant — AF-M315E — developed by the U.S. Air Force Research Laboratory in California. During the demonstration to be carried out by Ball Aerospace & Technologies Corp., of Boulder, Colorado, the spacecraft's five engines or thrusters built by Aerojet Rocketdyne, of Redmond, Washington, will burn in different operations, testing how reliably the engines perform.

For its part, Goddard carried out fluid testing on GPIM's systems and components, Bacha said. In particular, the test team carried out the first-ever "surge" and flow testing on AF-M315E. Surge is a phenomenon that occurs when an isolation valve opens to allow propellant to rapidly fill empty manifold lines. The resulting pressures, if too high, potentially can damage sensitive flight components downstream. Flow testing, meanwhile, reveals how individual components perform in a system using the propellant. No data of this type existed for the AF-M315E prior to Goddard's surge and flow testing.

"We have so many balls in the air with green propellant," Bacha said. "We appreciate the opportunity to get our hands dirty, so to speak, with these propellants."

Another Alternative

Although the more traditionally used hydrazine will not be completely displaced due to its long heritage and widespread use, the two green propellants do offer compelling advantages. In addition to being easier to handle, they are more tolerant of low temperatures and could bring about less-expensive, more flexible mission designs. Furthermore, both green propellants are better performing than hydrazine, meaning that a spacecraft could carry out more maneuvers on one tank of propellant or may not need to carry as much propellant. This would allow room for additional flight instruments.

"It's beneficial for us that we understand both," Mulkey said. "The change is coming." ❖

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Crunch Time

Two Goddard Teams Advancing Mission Concepts Under Phase-A Studies

It's crunch time for two Goddard teams now fine-tuning mission concepts. One would probe the Venusian atmosphere — the first U.S. effort to do so in nearly four decades — and the other would explore the shape of space distorted by a spinning black hole's gravity.

The teams, both led by Goddard scientists, have received NASA Phase-A mission funding to further develop their missions: the Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging, or DAVINCI, and the Polarimeter for Relativistic Astrophysical X-ray Sources (PRAXyS). DAVINCI is one of five concepts competing for full development as NASA's next Discovery mission, while PRAXyS is competing against two others for development as a NASA Small Explorer.

Another proposed mission with significant Goddard involvement is Lucy. Led by the Southwest Research Institute, Lucy would provide the first reconnaissance of the Jupiter Trojan asteroids. If selected, Goddard would manage the project.

"Although we wish all competitors well, we're particularly proud of the DAVINCI and PRAXyS teams," said Goddard Chief Technologist Peter Hughes, who manages the center's Internal Research and Development program. "We provided the initial seed funding that got these mission concepts started in the first place."

Although team members will not speculate on their chances of winning a mission, they are nonetheless optimistic.

DAVINCI

"We haven't sent a probe to Venus since 1978," said DAVINCI Principal Investigator Lori Glaze. Furthermore, the most recent mission to Venus, the European Space Agency's Venus Express, did not plunge through the planet's thick, high-pressure atmosphere, primarily comprised of sulfur. It gathered measurements above the clouds.

DAVINCI, on the other hand, would dispatch a probe on a 63-minute journey through the planet's atmosphere, winding up in the roughest and most geologically complex terrain on Venus — an area distinguished by crisscrossed ridges. "We don't know if these ridged highlands were formed because of buckling or if they are leftover continents," Glaze said. "They are the oldest terrain on Venus, but we really don't know what they are."

As the probe travels through the atmosphere, its onboard spectrometer would measure several noble gases — helium, neon, argon, krypton, and xenon — as well as trace gases, including water vapor, sulfur dioxide, and carbonyl sulfide with an unprecedented level of detail not possible with ear-

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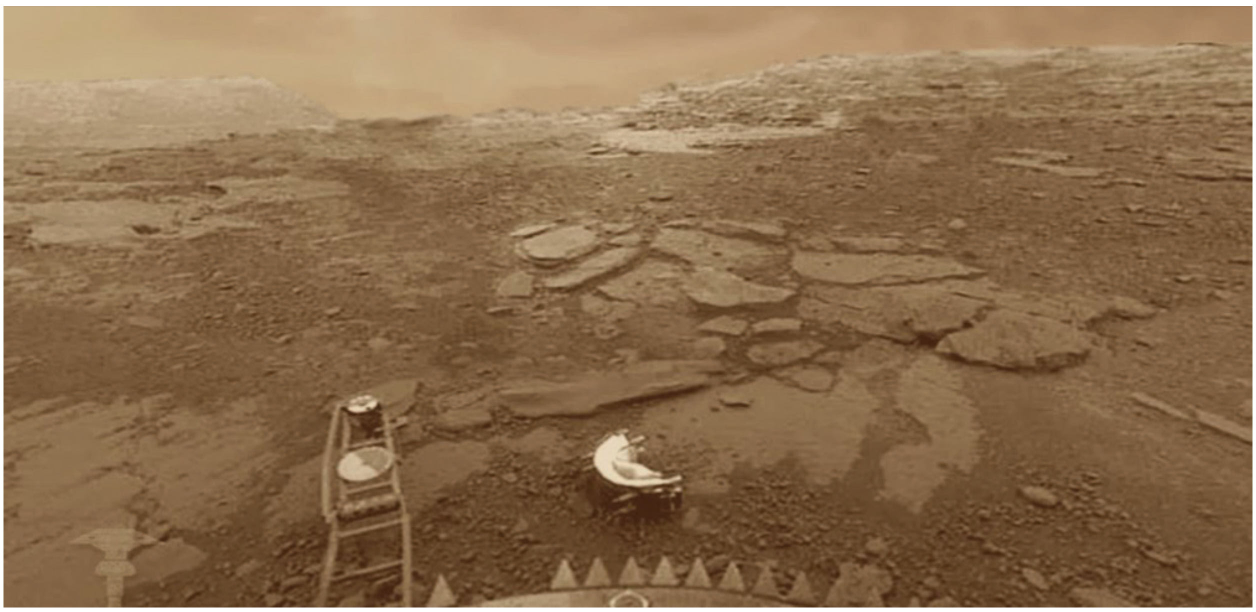
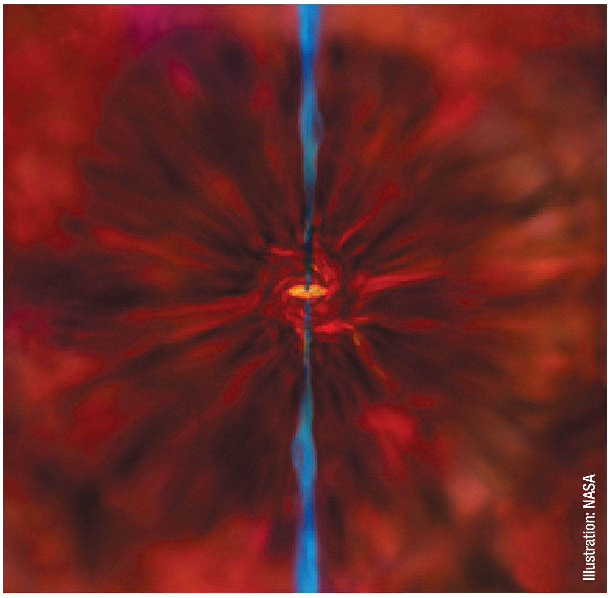


A Soviet-era lander snapped this photo of the Venusian surface. A NASA team would like to deploy its own probe to not only sample the planet's atmosphere, but also image its ridged terrain.

lier missions. These measurements would allow scientists to study how the Venusian atmosphere formed and then changed over time, including what happened to its water.

While previous missions have remotely sensed large quantities of sulfur in the planet's thick clouds, they did not reveal its source. "We also don't understand the sulfur cycle," Glaze said. "It has to come from somewhere." As a result, another key objective is discovering whether active volcanoes are contributing to these levels.



A proposed mission, called PRAXyS, would explore the shape of space distorted by a spinning black hole's gravity. This artist's rendition shows how material very near a black hole falls inward and joins a rapidly spinning disk of matter.

As the probe descends, its camera then would snap images of the targeted landing site, a NASA first. The former Soviet Union is the only space-faring nation that has actually imaged the surface, and the images its mission captured were of the flat and monotonous volcanic plains. "Our pictures will be the first-ever optical images of the complex ridged terrain," Glaze said.

"It's not a bells-and-whistles mission," she added. "But it will change the way we think about Venus. It could rewrite the textbooks."

PRAXyS

PRAXyS also is designed to provide never-before-obtained measurements: the shape of space that has been distorted by the gravity of a spinning black hole and the structure and effects of the magnetic field around neutron stars — the densest objects in the universe.

"We are in an excellent position, technically," said Principal Investigator Keith Jahoda.

Though tweaked, PRAXyS borrows heavily from Goddard's Gravity and Extreme Magnetism SMEX (GEMS), which NASA had selected for Phase-B development in 2009, but later cancelled. "The happy news is that we did most of the technology development under the GEMS effort. It's good. We're now able to capture these advances and make this exciting possibility happen," Jahoda said.

The proposed mission would give scientists a new view of high-energy objects that until now had been impossible to measure. Current missions, for example, cannot investigate the shape of space around spinning black holes because they do not have the required angular resolution. However, PRAXyS will employ a new technique. It will indirectly measure the polarization of X-rays with greater sensitivity than any previous X-ray polarization experiment.

Like all light, X-rays have a vibrating electric field. The field is perpendicular to the direction of the X-ray, but can be in any direction: up and down, side to side, or at any angle in between. If the X-ray source is uniform, the electric field can take any direction. However, for non-uniform sources, such as the accretion disk around a black hole or a hot spot on the surface of a neutron star, the electric field will take a preferred direction. This is called polarization. Measuring the preferred direction and the strength of that preference provides clues to the structure of the source.

The heart of the mission is a small chamber filled with gas. When an X-ray is absorbed in the gas, an electron carries off most of the energy and starts out in a direction related to the polarization direction of the X-ray. This electron loses energy by ionizing the gas. The instrument then measures the direction of the ionization track, and thereby the polarization of the X-ray.

Measuring polarized X-rays can reveal the geometry of matter as it's ejected from a black hole, determining whether the matter is confined to a flat disk, puffed into a sphere, or expelled in a jet.

Three mission teams are vying for the Small Explorer opportunity. NASA is expected to choose the winner in 2017. "We can guarantee we will write an exciting proposal that will be within the price cap," Jahoda said. ❖

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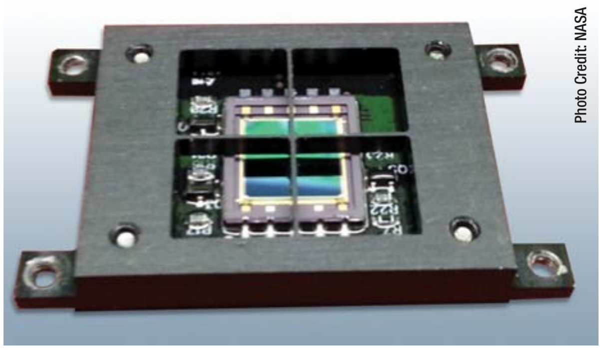
CubeSat Mission, *continued from page 9*

Developed at the Wallops Flight Facility in Virginia's Eastern Shore, the sun sensor calculates a direction to the sun. The mCAT system, which is about the size of a coffee mug, fires its thrusters to move the spacecraft so that it maintains its alignment with the smaller CubeSat separated by nearly 33 feet.

Under the collaboration established by the international agreement, Yonsei and KARI are providing the two spacecraft, integrating the Goddard-supplied sun sensor and mCAT system, and launching the spacecraft.

"We want to show that the architecture works," Shah explained. "We have all the technology to keep the spacecraft aligned." Once he and his partners show the capability, they plan to prepare another mission that would gather scientific data. "Once we do this modest demonstration, we can scale up. We're taking baby steps." ❖



This is a closeup of the Wallops-developed fine sun sensor that is flying on the CANYVAL-X mission.

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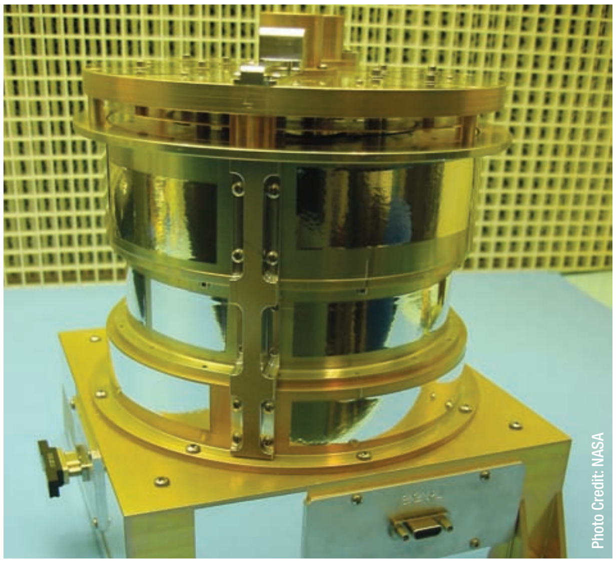
Mission Names, *continued from page 12*



One of HALO's instruments, the Energetic Neutral Analyzer, borrows heavily from a previous instrument that Principal Investigator Michael Collier and his team flew on an Air Force-sponsored small-satellite mission called FASTSAT, which launched about four years ago. The instrument is shown here.

Baryonic matter makes up about 4.9 percent of the total mass-energy of the universe. However, a tally of luminous matter fails to locate a substantial fraction of the predicted baryons, leading to the "missing baryon" problem.

The aim of HaloSat is to determine whether the missing baryons are gravitationally bound to galaxies or instead form an intergalactic medium.

One possible reservoir of missing baryons associated with the Milky Way is an extended halo of very hot X-ray emitting gas. With HaloSat, the team will map the distribution of hot gas in the Milky Way halo using the emission of highly ionized oxygen as a tracer. If the missing baryons are indeed in the Milky Way halo, HaloSat should detect them. A non-detection would point to a diffuse and intergalactic medium. ❖

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Cutting edge Goddard's Emerging Technologies

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