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Cutting edge
Goddard's Emerging Technologies

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Planting More Than a Footprint

SPECIAL REPORT
Preparing for the Next Steps in Human Exploration

This year, NASA celebrates the 50th anniversary of the Apollo 11 moon landing. Efforts are now underway to return humans to the Moon and ultimately Mars, with significant help from the commercial sector. In these stories appearing on pages 2, 5, 8, 9, and 11, CuttingEdge reports on the role Goddard will likely play in this new era of exploration and the technologies center scientists and engineers are now developing to assure a more permanent human presence on the Moon and other solar system bodies.

Planting More Than a Footprint

Goddard Prepares for a New Era of Human Exploration of the Moon and Points Beyond

As NASA celebrates the golden anniversary of the first Moon landing later this year, scientists, engineers, and technologists are preparing for a new era of human exploration, which includes a new launch system and a lunar-orbiting outpost that will serve as the jumping-off point for human spaceflight deeper into the solar system.

As it did 50 years ago, Goddard is playing a vital role in these initiatives, particularly in the areas of communications and instrument development as evidenced by the recent award of five proposals to advance spacecraft-based instruments for use in lunar-landing missions (see story, page 5).

However, technology and priorities have changed since Apollo 11. NASA is pursuing a more permanent presence, which envisions heavy involvement by the commercial sector. The technologies that will return humans to the Moon and beyond will have to be more powerful and multipurpose, said Jake Bleacher, lead exploration scientist responsible for identifying areas where Goddard scientists can support human exploration.

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About the Cover

Neil Armstrong may have been the first man to step foot on the Moon, but it was Buzz Aldrin who appeared in most of the Apollo 11 photos. That's because Armstrong carried the 70-millimeter Hasselblad camera with which he snapped photos, including this iconic image of Aldrin's footprint in the lunar regolith. As NASA celebrates the golden anniversary of the first Moon landing at the Sea of Tranquility on July 20, 1969, the agency and Goddard are preparing for a new era of human exploration featuring a lunar-orbiting space station and other assets that could afford a more permanent presence in the exploration of the Moon and points beyond.

Photo Credit: NASA

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"Houston may have broadcast Neil Armstrong's first words, but they had to first come through Goddard's communications hub," added Noah Petro, the project scientist on the Lunar Reconnaissance Orbiter, or LRO, which has thoroughly mapped the lunar surface — data that will inform future Moon landings (see related story, page 8). "But I want to stress that Goddard's role in human spaceflight isn't limited to communications. During the Apollo era, we developed instrument packages. That role will continue."

Transition to Laser Communications

Without question, Goddard's legacy role of providing communications between the ground and next-generation spacecraft will continue to be one of the center's most significant contributions to future exploration with NASA's Space Launch System, Orion Multipurpose Crew Vehicle, and Lunar Orbital Platform, known as Gateway, Petro said.

But the radio frequency (RF)-based systems of yore, which 50 years ago consisted of a vast network of ground antennas and land lines, and more recently NASA's Tracking and Data Relay Satellites, or TDRS, are giving way to optical or laser communications, known as laser comm. Although RF-based systems will continue playing a role, the transition is motivated by the agency's ever-increasing demand for high-definition video and increased data loads.

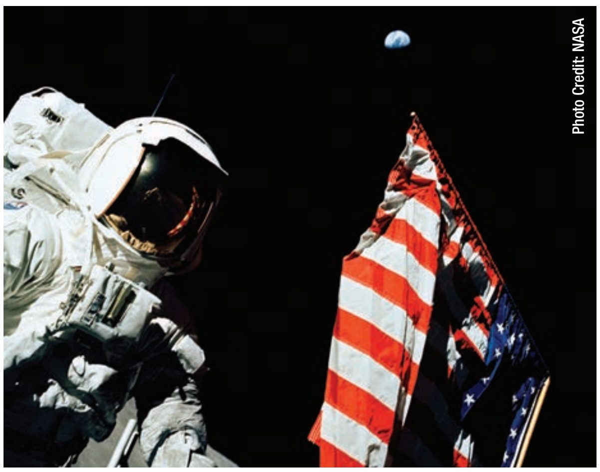

Photo Credit: NASA

Geologist-Astronaut Harrison Schmitt, Apollo 17 Lunar Module pilot, is photographed next to the American flag during NASA's final lunar landing mission in the Apollo series — a mission that included an instrument developed by Goddard scientist Otto Berg. The photo was taken at the Taurus-Littrow landing site. The highest part of the flag appears to point toward planet Earth in the distant background.

Photo Credit: NASA

Apollo 11 Astronaut Buzz Aldrin moves toward a position to deploy two components of the Early Apollo Scientific Experiments Package, or EASEP, on the lunar surface.

To prove a fully operational laser-comm system, Goddard is expected to launch the Laser Communications Relay Demonstration, or LCRD, mission aboard a U.S. Air Force spacecraft, which will operate 22,000 miles above Earth's surface in geosynchronous orbit. Over the mission's lifespan, LCRD will relay data encoded onto beams of infrared light initially between two Earth terminals in California and Hawaii.

In 2021, NASA will up the ante. NASA is expected to deploy its first low-Earth-user modem, called ILLUMA-T, on the International Space Station (ISS). There, the Goddard-developed technology will serve as a laser-comm terminal for ISS, communicating data from low-Earth orbit to the ground through the LCRD relay. This will demonstrate the potential for laser communications at rates that are 10 to 100 times better than RF systems, using less power and mass.

And about two years later, the Goddard-developed Orion EM-2 Optical Communications System will provide high-speed data and high-definition video

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streaming for up to an hour each day during NASA's first manned flight of the Orion Multipurpose Crew Vehicle to lunar orbit. After the initial mission, Goddard technologists expect to add more laser-comm terminals on future Orion exploration flights.

The evolution from RF-based systems to optical also includes the addition of a terminal on the Lunar Orbital Platform, known as Gateway. This lunar-orbiting outpost will act as a basecamp to explore the surface of the Moon, conduct experiments, and prepare for spaceflights to more distant destinations.

Goddard will provide laser-communications services to NASA's Orion vehicle, shown in this artist concept.

Adding laser-comm capabilities on next-generation relay satellites in geosynchronous orbit — similar to the RF-based TDRS constellation — also is part of the plan. "We're also working to develop the next-generation of relay satellites that provide optical services," said Dave Israel, a communications architect for Goddard's Exploration and Space Communications division.

The New Normal: Multipurpose Scientific Instruments

For scientific investigations, NASA's Gateway, which NASA plans to begin assembling in 2022, will likely be a focal point. To be positioned in an orbit high above the lunar poles, Gateway will be smaller than the low-Earth-orbiting ISS, but like the space station, include docking and mounting points for instruments.

"We're trying to get science infused early in Gateway's development," Bleacher said, adding that he's building awareness among Goddard's scientists of the platform's capabilities.

But Bleacher said the focus will be different this time. Future instruments must be used for multiple purposes. "Our job is to think of other ways that a science instrument could be used by NASA's Human Exploration and Operations Mission Directorate," Bleacher said.

A good example of this multipurpose philosophy is the Goddard-developed Neutron star Interior Composition Explorer, or NICER, Bleacher said. Although designed primarily to study neutron stars, NICER also carries built-in software that uses timing data from pulsing neutron stars to stitch together autonomous navigational solutions. The experiment, called the Station Explorer for X-ray Timing and Navigation Technology, or SEXTANT, proved the capability in late 2017 (*CuttingEdge*, Winter 2018, Page 2).

This year, NICER Principal Investigator Keith Gendreau and his team are expected to showcase yet another potentially groundbreaking technology with the NICER payload — X-ray communications, or XCOM, in space (see related story, page 9). Although very early in its development, XCOM could usher in the next generation of communications technologies.

"NICER is the model we want to apply to everything," Bleacher said. "My goal is to maximize the time of use for any technology we develop. Instead of building a butcher knife for a unique and single purpose, let's send a Swiss army knife that can accomplish many different tasks. That's where exploration gets interesting." ❖

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SPECIAL REPORT
Preparing for the Next Steps in Human Exploration

When the Call Comes, Goddard Lunar Scientists Will Be Ready

Five Teams Win NASA DALI Awards to Advance Future Lunar Missions

When NASA solicits future investigations of the Moon — something that could happen as early as 2023 — five teams involving Goddard scientists and engineers will be ready.

The agency's Development and Advancement of Lunar Instrumentation, or DALI, program recently awarded 10 teams each about $4 million in funding to mature spacecraft-based instruments for use in future lander missions including those offered by commercial ventures. These instruments, which are supposed to have reached a high level of technology readiness by the time funding ends in three years, will support scientific investigations, human exploration, lunar mining, and other in-situ lunar-resource activities.

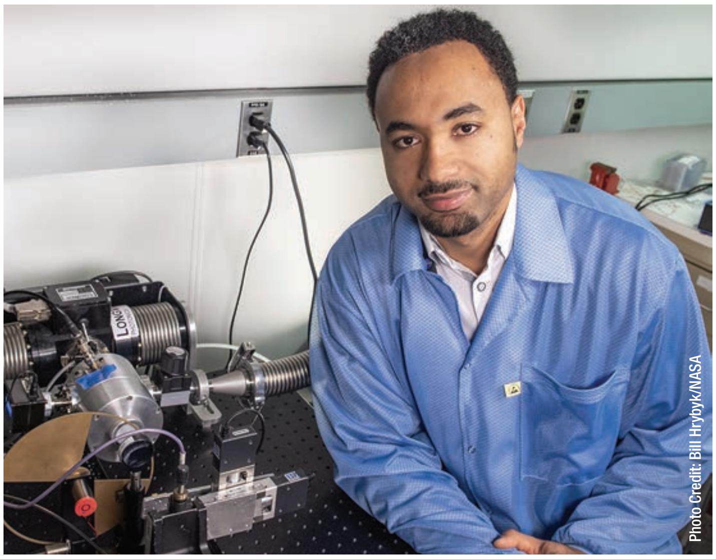
Photo Credit: Bill Hrybyk/NASA

Goddard engineer Berhanu Bulcha is developing with internal R&D funds a critical technology, a terahertz mixer, for one of the submillimeter spectrometers being developed for the conceptual SSOLVE mission, which would investigate water on the Moon.

Of the 10 awards, half went to teams involving Goddard experts, who are either serving as principal investigators or co-investigators — a success rate that didn't escape many.

"The new DALI program is designed to advance and mature instrument prototypes to the point where they could be selected for flight once NASA issues solicitations for lunar instruments," said Brook Lakew, associate director for planning and R&D for Goddard's Solar System Exploration Division. "The fact that our scientists and engineers — many of whom used internal R&D seed funding to start work on their concepts — won five of those awards assures that Goddard will have a role to play in NASA's new era of exploration. Our teams certainly made an admirable showing in this round of the DALI competition."

Submillimeter Solar Observation Lunar Volatiles Experiment (SSOLVE)

Since 2008, when scientists first discovered water in the Moon's thin atmosphere and then recently reconfirmed its presence on the surface particularly at the poles, Earth's only orbiting natural orb has become a decidedly more interesting place. It's not the dry bone scientists first thought it to be. SSOLVE, led by University of Maryland researcher Timothy Livengood, with significant participation from Goddard engineers and scientists, is being designed to investigate the origin of this water.

The goal is to answer questions about its presence both in the atmosphere and at the poles, determining if solar wind or meteoroids deliver the water or if it's created indigenously through different chemical processes involving the Sun. The team also wants to confirm whether it exists primarily as water molecules or as hydroxyl radicals and how it's lost. Answers to these questions would have powerful implications concerning the Moon's formation and evolutionary processes, Livengood explained.

"The discovery of water was shocking," Livengood said, adding that the SSOLVE concept leverages several technologies and mission concepts developed at Goddard, including two CubeSat missions and a digital spectrometer developed for the proposed Submillimeter Enceladus Life Fundamentals Instrument, or SELFI, which would measure that moon's icy plumes (*CuttingEdge*, Fall 2017, Page 9).

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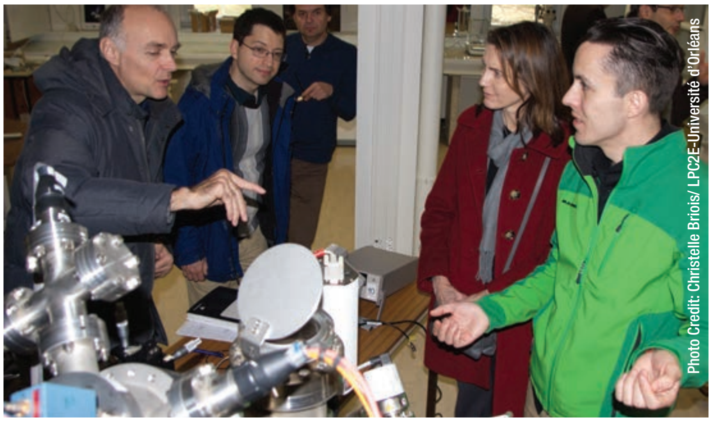
SELFI's developer, Goddard scientist Gordon Chin, is serving as an instrument co-investigator.

With its two spectrometers tuned to submillimeter and terahertz wavelengths ideal for detecting water, SSOLVE would be deployed on a lander, where it would use the Sun as a light source to illuminate the presence of water in the Moon's tenuous atmosphere, specifically measuring the abundances and the chemical state of water, hydroxyl, and heavy water and how these levels vary over time.

"Now we're going after the fundamentals; we're trying to get the lay of the land," Livengood added. "Could we use the water during human exploration of the Moon?"

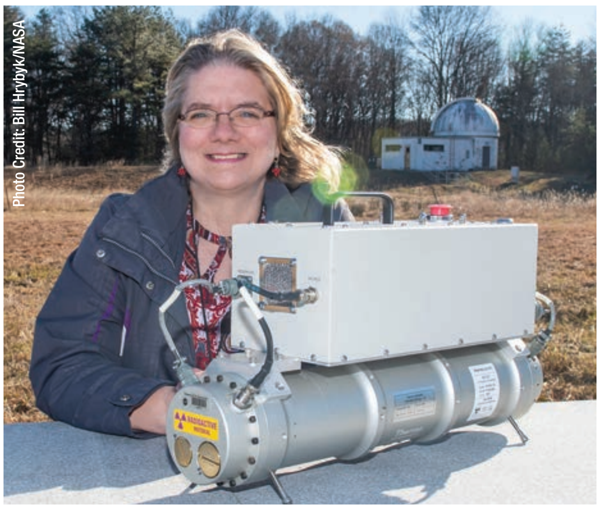


Principal Investigator Ricardo Arevalo (right), Adrian Southard (center), and Cynthia Gundersen (standing next to Arevalo) are members of the international CRATER development team, which met in France earlier in 2018 to discuss the CosmOrbitrap mass analyzer, a key CRATER instrument.

Characterization of Regolith and Trace Economic Resources (CRATER)

CRATER Principal Investigator Ricardo Arevalo, a former Goddard scientist and now a professor at the University of Maryland, is working with a global team, including experts at Goddard and various laboratories in France, to develop an advanced laser-based mass spectrometer aimed at redefining scientists' understanding of the Moon's composition.

In addition to investigating how the Moon formed, CRATER would catalog non-native organic compounds and prospect for valuable metals, such as titanium, iron, chromium, and copper.



Goddard scientist Ann Parsons is pictured with a commercial version of the Pulsed Neutron Generator that she will be maturing for use on her BECA instrument, which will be tested at a granite formation located at Goddard's Geophysical and Astronomical Observatory.

Conceived as a lander-payload instrument, CRATER pioneers two cutting-edge subsystems: a Goddard-developed, high-power, solid-state ultraviolet laser that converts a sample's molecules into ions that are then directed into a state-of-the-art CosmOrbitrap mass analyzer developed by the team's French partners. The instrument would produce high-resolution spectra that reveal far greater details about the components making up the sample.

"When our effort is done, hopefully we'll have an opportunity to go to the Moon, but CRATER could be reconfigured for any airless body," Arevalo said.

Bulk Elemental Composition Analyzer (BECA)

BECA is a lander instrument capable of determining the bulk elemental composition of material found on the Moon's surface as well as that located about eight inches (20 centimeters) beneath it.

Conceived a decade ago by Goddard Principal Investigator Ann Parsons, BECA is designed to pulse neutrons into the regolith (Goddard Tech Trends, Summer 2009, Page 6). When these neutrons interact with an element's nucleus, the nucleus becomes excited and emits gamma rays, which a spectrometer would detect to reveal the presence of elements, including hydrogen, oxygen, aluminum, silicon, titanium, and iron, among many others.

The beauty of BECA is that it would do its sleuthing without moving parts and would not physically interact with the lunar terrain when gathering mea-

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surements. Furthermore, low-energy neutrons are also emitted by the lunar surface. Measurements by BECA's neutron detectors would allow for more sensitive and deeper measurements of hydrogen — an important ingredient in water — than from gamma rays alone.

According to Parsons, NASA has never flown an instrument quite like BECA, which could operate statically or on a rover. "I've tried to get this funded for a long time," she said. "The DALI funding will mature the instrument to the point where it can fly without additional developments."

Potassium-Argon Laser Experiment (KArLE)

Determining the age of lunar rocks is the primary purpose of KArLE, a proposed rover instrument conceived by Goddard scientist Barbara Cohen.

According to her, knowing the precise ages afforded through potassium-argon dating — the method of determining a rock's time of origin by measuring the ratio of radioactive potassium to its daughter product, argon — will help scientists understand the Moon's history, its formation, the effects of bombardment, and by extension, the history of the solar system. Currently, radiometric dating can only be done on samples returned to Earth-based laboratories.

"A capability such as KArLE is crucial because we can't possibly bring back samples from everywhere on the Moon," said Cohen, whose team includes several Goddard engineers, the University of Maryland, Los Alamos National Laboratory, and Honeybee Robotics.

To get these measurements, KArLE would use imaging, visible-light spectrometry, which analyzes light broken down into its component colors, and mass spectrometry, the method for identifying samples by obtaining their masses. These techniques are employed on instruments currently operating on the Curiosity rover. With her three-year funding, she will integrate these analytical components, along with a sample-handling system, into a prototype and subject it to environmental testing.

Lunar Environment Monitoring Station (LEMS)

LEMS is a compact, long-duration surface station that would spend at least two years monitoring the exosphere, the thin atmosphere surrounding the Moon. Previous missions have identified short-

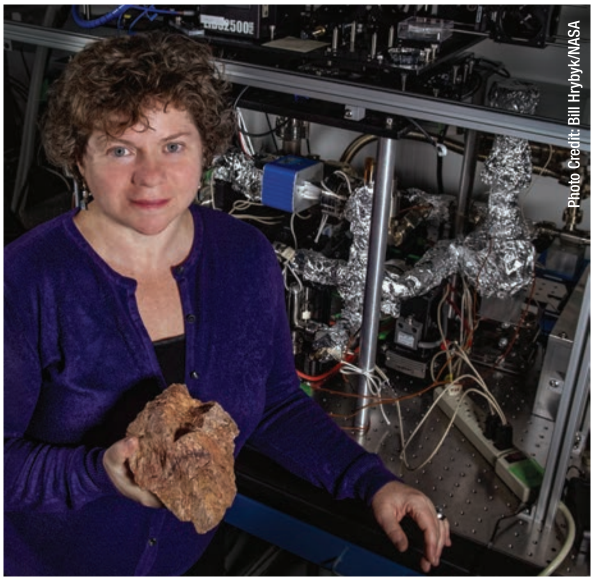

Photo Credit: Bill Hrybyk/NASA

KArLE is an instrument now being developed by Goddard scientist Barbara Cohen. Cohen is pictured with a laboratory breadboard of her instrument and a rock from the Santa Fe impact crater, which experienced the same conditions of rocks she wants to date on the Moon.

term changes in the exosphere, but NASA has never landed an instrument capable of longer-term research. It will also listen to the Moon's seismic activities to better understand the structure of the Moon's interior. NASA stopped collecting seismic data when the Apollo seismographs stopped working in 1977.

Like many of the other DALI proposals, it, too, takes advantage of heritage instruments, said Co-Investigator Charles Malespin, a Goddard scientist assisting in the effort led by Mehdi Benna, a researcher at the University of Maryland.

It makes use of Goddard-developed CubeSat and SmallSat subsystems that would generate and distribute power to the station's neutral mass spectrometer, which is identical in design to the one flown on NASA's Lunar Atmosphere Dust and Environment Explorer, or LADEE, and the Mars Atmosphere and Volatile Evolution Mission, known as MAVEN. LEMS would also include a low-power seismometer, which would provide the building blocks for a larger seismographic and geophysical network. ❖

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SPECIAL REPORT

Preparing for the Next Steps in Human Exploration

Snapshot of Goddard's Past Lunar Instruments and Missions

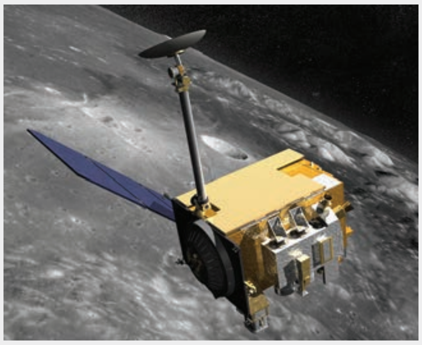
Goddard's preparation for the next era of exploration isn't without precedent. Here's a snapshot of some of the instruments and missions that center scientists and engineers developed or participated in during and following the Apollo years.

Lunar Ejecta and Meteorites Experiment (LEAM)

Developed by Goddard scientist Otto Berg, LEAM was deployed on Apollo 17, the final mission of the Apollo program in December 1972. LEAM studied the nature of small particles striking the Moon to determine their speed and direction. LEAM primarily detected fine dust grains being transported at slow speeds across the lunar surface.

Clementine

Goddard supported the development of the laser altimeter that flew on Clementine. Launched on January 25, 1994, the joint military-NASA mission provided the first complete look at the lunar surface, finding evidence suggesting the presence of water-ice at the south pole.



Lunar Reconnaissance Orbiter (LRO)

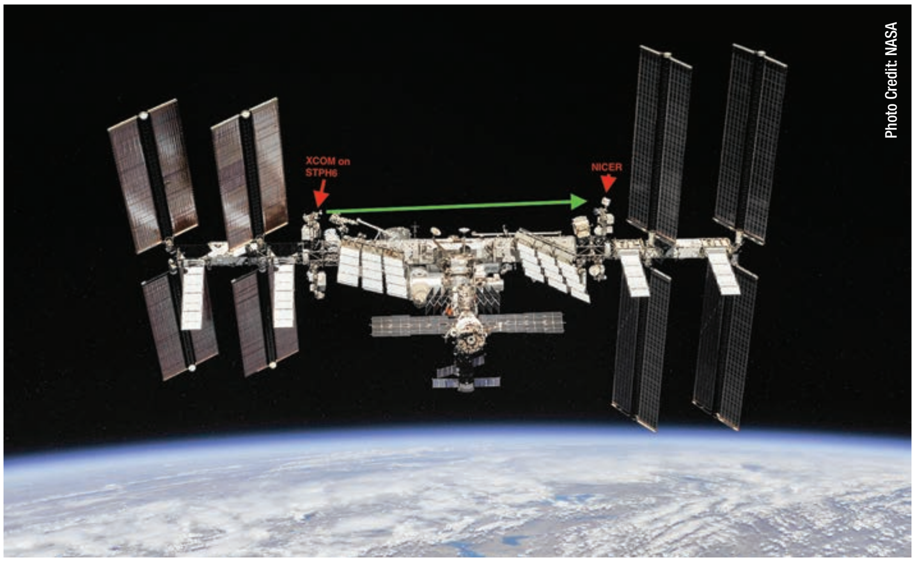
LRO — Goddard's first managed planetary mission — launched on June 18, 2009, along with the Lunar CRater Observation and Sensing Satellite, or LCROSS, which confirmed water-ice at the Moon's south pole. One of LRO's seven instruments was the Goddard-developed Lunar Orbiter Laser Altimeter (LOLA), which mapped the Moon's topography, providing critical data necessary to select intriguing, safe landing sites as well as references needed to navigate to those sites. Goddard also supported the Russian-provided Lunar Exploration Neutron Detector (LEND), which created high-resolution maps of hydrogen distribution.

Lunar Atmosphere and Dust Environment Explorer (LADEE)

For LADEE, Goddard managed its three scientific instruments, including the Goddard-built Neutral Mass Spectrometer, and its technology-demonstration payload, the Lunar Laser Communications Demonstration (LLCD). LLCD made history using a pulsed laser beam to transmit data over the 239,000 miles from the Moon to the Earth at a record-breaking download rate of 622 megabits-per-second.

NASA Set to Demonstrate X-ray Communications in Space

A cargo-supply vehicle carrying hardware vital to NASA's first demonstration of X-ray communications in space is set to launch to the International Space Station in late April.



NASA's first-ever demonstration of X-ray communications will occur on the International Space Station. This image shows the locations of the MXS and the NICER payload, which are critical to the demonstration.

"We've waited a long time to demonstrate this capability," said Jason Mitchell, a Goddard engineer who helped develop the technology demonstration that relies on the Modulated X-ray Source, or MXS. MXS is a key component in the demonstration that will likely happen shortly after the SpaceX Dragon vehicle delivers the device to the orbiting outpost in April. It's one of many experiments packaged on the U.S. Air Force's Space Test Program-Houston 6 (STP-H6) experiment pallet.

"As soon as we're ready, we'll do this demo as quickly as we can," Mitchell said.

If successful, the experiment could generate even greater interest in the communications technology, which could permit more efficient gigabit-per-second data rates for deep-space missions.

XCOM, as it's also known, could in the future supplant emerging laser- or optical-communications systems, Mitchell said. It offers several advantages. X-rays have much shorter wavelengths than visible or infrared light typically used in laser-communications systems. This means that XCOM can send more data for the same amount of transmission power because X-rays can be broadcast in tighter beams, thus using less energy when communicating over vast distances.

"For some missions, like those measuring solar gravitational lensing, XCOM may be an enabling technology due to the extreme distances where they must operate," Mitchell said.

Perhaps more dramatically — at least as far as human spaceflight is concerned — X-rays can pierce the hot plasma sheath that builds up as spacecraft hurdle through Earth's atmosphere at hypersonic speeds — that is, five or more times the speed of sound. The plasma acts as a shield, cutting off radio-frequency communications with anything outside the vehicle for several seconds — a nail-biting period of time dramatically portrayed in the movie, Apollo 13. Thus, XCOM would enable full communications during reentry.

Because no one has ever used X-rays in a communications system, other applications not yet conceived could emerge, he said. "The challenge in the immediate future will be getting others interested in further developing this technology," Mitchell said.

MXS to Encode Digital Bits

To demonstrate this potentially game-changing communications technology, the NASA team will use the MXS to generate rapid-fire X-ray pulses. Operated by another Goddard-developed computing and navigation technology called NavCube, MXS will turn on and off many times per second while encoding digital bits for transmission.

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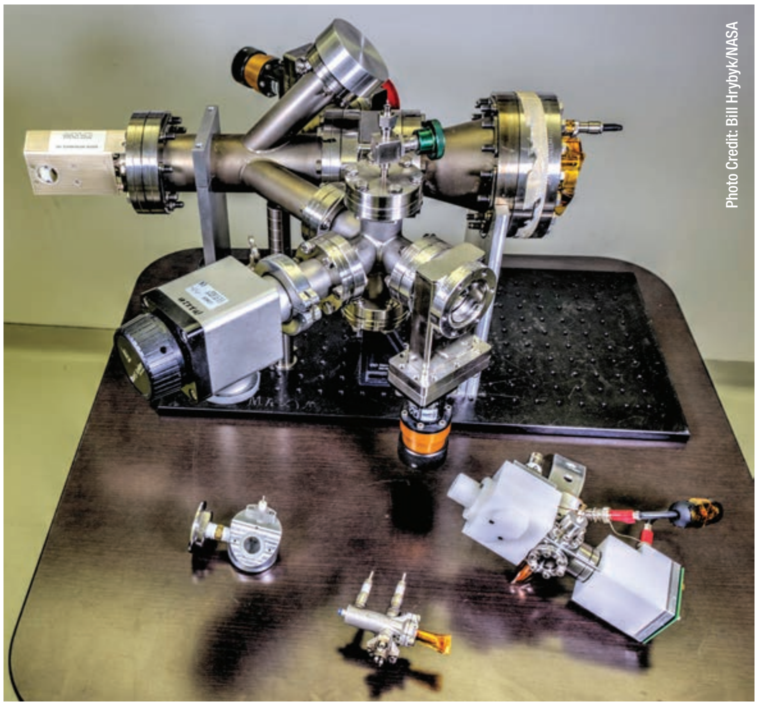
From the experimental payload on the STP-H6 pallet, MXS will then send the encoded data via the modulated X-rays to detectors on the Neutron-star Interior Composition Explorer, or NICER, which is located 165 feet away — a distance roughly the width of a football field — on the space station truss. In this way, NICER becomes the receiver of a one-way X-ray signal.



This image shows the MXS, a key component in NASA's first-ever demonstration of X-ray communications in space.

Although the first XCOM test will involve the transmission of GPS-like signals, Mitchell said he and his team may attempt to transmit something more complicated after the initial attempt. "What's important is that we transmit a known code we can identify to make sure NICER receives the signal precisely the way we sent it," Mitchell said.

Although primarily built to gather data about the densest objects in the universe — neutron stars and their pulsating next-of-kin, known as pulsars — NICER was also designed to demonstrate advanced technology. In addition to the XCOM demonstration, the mission proved in 2017 the effectiveness of X-ray navigation, or XNAV, in space, showing that pulsars could be used as timing sources for navigational purposes (*CuttingEdge*, Winter 2018, Page 2).

During that two-day demonstration, which the NICER team carried out with an experiment called Station Explorer for X-ray Timing and Navigation Technology, or SEXTANT, the mission gathered 78 measurements from four millisecond pulsars. The team fed that data into onboard algorithms to autonomously stitch together a navigational solution that revealed the location of NICER in its orbit around Earth as a space station payload. Within eight hours of starting the experiment, SEXTANT converged on a location within the targeted 6.2 miles and remained well below that threshold for the rest of the experiment.

NICER's ability to carry out science and demonstrate emerging, revolutionary technologies has captured the attention of those planning NASA's next era of human spaceflight. Missions that perform multiple functions are now considered a model (see page 2), said Jake Bleacher, lead exploration scientist responsible for identifying areas where Goddard scientists can support human exploration of the Moon and Mars.

XCOM Heritage: Black Hole Imager

The XCOM and XNAV ideas originated more than a decade ago when NICER Principal Investigator Keith Gendreau began work on enabling technologies for a proposed black hole imager aimed at directly imaging the event horizon of a supermassive black hole or the point of no return where nothing — neither particles nor photons — can escape.

The idea was to establish a constellation of precisely aligned spacecraft that would in essence create an X-ray interferometer, an instrument used to measure displacements in objects. He conceived the idea of using X-ray sources as beacons to enable highly precise relative navigation. Using R&D funding, Gendreau developed the MXS.

Gendreau then reasoned that if he could modulate X-rays through a modulator, he could also communicate, thus giving birth to the NICER three-in-one mission concept. ❖

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SPECIAL REPORT
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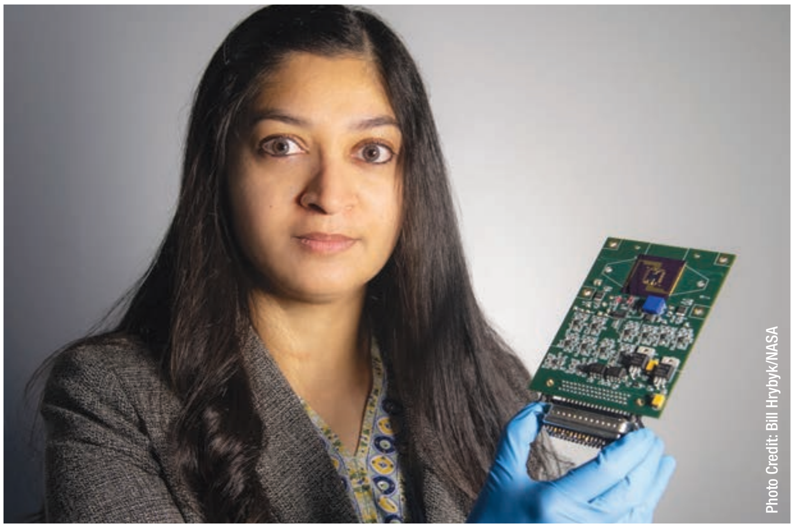
Taking Miniaturization to the Extreme

Goddard Technologist to Advance Multifunctional Sensor Platform

A Goddard technologist is taking miniaturization to the extreme.

Mahmooda Sultana won funding to advance a potentially revolutionary, nanomaterial-based detector platform. The technology is capable of sensing everything from minute concentrations of gases and vapor, atmospheric pressure and temperature, and then transmitting that data via a wireless antenna — all from the same self-contained platform that measures just two-by-three-inches in size.



Technologist Mahmooda Sultana holds an early iteration of an autonomous multifunctional sensor platform, which could benefit all of NASA's major scientific disciplines and efforts to send humans to the Moon and Mars.

Under the $2-million technology-development award, Sultana and her team will spend the next two years advancing the autonomous multifunctional sensor platform, which if successful, could benefit all of NASA's major scientific disciplines and efforts to send humans to the Moon and Mars. These tiny platforms could be deployed on planetary rovers to detect small quantities of water and methane, for example, or be used as monitoring or biological sensors to maintain astronaut health and safety.

Central to the effort, funded by NASA's Space Technology Mission Directorate's (STMD) Early Career Initiative (ECI), is a 3-D printing system developed by Ahmed Busnina and his group at Boston's Northeastern University, or NEU. The 3-D printing system is like offset printers used to produce money or newspapers. However, instead of ink, the printer applies nanomaterials, layer-by-layer, onto a substrate to create tiny sensors. Ultimately, each is capable of detecting a different gas, pressure level, or temperature.

Nanomaterials, such as carbon nanotubes, graphene, molybdenum disulfide, and others, exhibit interesting physical properties. They are highly sensitive and stable at extreme conditions. They are also lightweight, hardened against potentially damaging space radiation, and require less power, making them ideal for space applications, Sultana said.

Under her partnership with NEU, Sultana and her group will design the sensor platform, determining which combination of materials is best for measuring minute concentrations of water, ammonia, methane, and hydrogen in the parts per billion — all important in the search for life on other solar system bodies. Using her design, NEU will then use its Nanoscale Offset Printing System to apply the nanomaterials. Once printed, Sultana's group will functionalize the individual sensors by depositing additional layers of nanoparticles to enhance their sensitivity, integrate the sensors with readout electronics, and package the entire platform.

The approach differs dramatically from how technologists currently fabricate multifunctional sensor platforms. Instead of building one sensor at a time and then integrating it to other components, 3-D printing allows technicians to print a suite of sensors on one platform, dramatically simplifying the integration and packaging process, Sultana explained.

Also innovative is Sultana's plan to print on the same silicon wafer partial circuitry for wireless communications, further simplifying instrument design and construction. Once printed, the sensors and wireless antenna will be packaged onto a printed circuit board that holds the electronics, a

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power source, and the rest of the communications circuitry.

"The beauty of our concept is that we're able to print all sensors and partial circuity on the same substrate, which could be rigid or flexible. We eliminate a lot of the packaging and integration challenges," Sultana said. "This is truly a multifunctional sensor platform. All my sensors are on the same chip, printed one after another in layers."

Wide-Ranging Uses

The research picks up where other NASA-funded efforts ended. Under several previous efforts funded by Goddard's Internal Research and Development (IRAD) program and STMD's Center Innovation Fund (CIF), Sultana and her team used the same technique to manufacture and demonstrate individual sensors made of carbon nanotubes and molybdenum disulfide, among other materials. "The sensors were found to be quite sensitive, down to low parts per million. With ECI we are targeting parts-per-billion sensitivity by improving sensor design and structure," Sultana said.

According to her, the project addresses NASA's need for low-power, small, lightweight, and highly sensitive sensors that can distinguish important molecules other than by measuring the masses of molecules' fragments, which is how many missions currently detect molecules today using mass spectrometers.

In fact, the agency has acknowledged that future sensors need to detect minute concentrations of gases and vapors in the parts-per-billion level. Although mass spectrometers can detect a wide spectrum of molecules — particularly useful for unknown samples — it is difficult distinguishing between some of the important species, such as water, methane, and ammonia. "It's also difficult to reach the parts-per-billion or beyond level with them," she said.

"We're really excited about the possibilities of this technology," Sultana said. "With our funding, we can take this technology to the next level and potentially offer NASA a new way to create customized, multifunctional sensor platforms, which I believe could open the door to all types of mission concepts and uses. The same approach we use to identify gases on a planetary body also could be used to create biological sensors that monitor astronaut health and the levels of contaminants inside spacecraft and living quarters." ❖

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Goddard-Industry Team Creates and Demonstrates First Quantum Sensor for Satellite Gravimetry

Goddard and the Sunnyvale, California-based AOSense, Inc., have successfully built and demonstrated a prototype quantum sensor capable of obtaining highly sensitive and accurate gravity measurements — a stepping stone toward next-generation geodesy, hydrology, and climate-monitoring missions in space.

The prototype sensor employs a revolutionary measurement technique called atom interferometry, which former U.S. Energy Department Secretary Steven Chu and his colleagues invented in the late 1980s. In 1997, Chu received the Nobel Prize in Physics for his work.

Since the discovery, researchers worldwide have attempted to build practical, compact, more sensitive quantum sensors, such as atom interferometers, that scientists could use in space-constrained areas, including spacecraft.

With funding from NASA's Small Business Innovative Research, Instrument Incubator, and Goddard's Internal Research and Development programs, the Goddard-AOSense team developed an atom-optics gravity gradiometer primarily for mapping Earth's time-varying gravitational field (*CuttingEdge*, Fall 2013, Page 6). Although Earth's gravitational field changes for a variety of reasons, the most significant cause is a change in water mass. If a glacier or an ice sheet melts, this would affect mass distribution and therefore Earth's gravitational field.

"Our sensor is smaller than competing sensors with similar sensitivity goals," said Babak Saif, a Goddard optical physicist and collaborator in the effort. "Previous atom interferometer-based instruments included components that would literally fill a room. Our sensor, in dramatic comparison, is compact and efficient. It could be used on a spacecraft to obtain an extraordinary data set for understand-

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ing Earth's water cycle and its response to climate change. In fact, the sensor is a candidate for future NASA missions across a variety of scientific disciplines."

Atom interferometry works much like optical interferometry, a 200-year-old technique used in science and industry to measure small displacements in objects. Optical interferometry obtains measurements by comparing light that has been split between two different paths. When the beams from these two paths recombine, they create an interference-fringe pattern that scientists inspect to obtain highly precise measurements.

Atom interferometry, however, hinges on quantum mechanics, the theory that describes how matter behaves at sub-microscopic scales. Atoms, which are highly sensitive to gravitational signals, can also be cajoled into behaving like light waves. Special pulsing lasers can split and manipulate atom waves to travel different paths. The two atom waves will interact with gravity in a way that affects the interference pattern produced once the two waves recombine. Scientists can then analyze this pattern to obtain an extraordinarily accurate measure of the gravitational field.

In particular, the team is eying its quantum sensor as a potential technology to gather the type of data currently produced by NASA's Gravity Recovery and Climate Experiment (GRACE) Follow-On mission. GRACE-FO is a two-satellite mission that has generated monthly gravity maps showing how mass is distributed and how it changes over time. Due to its extraordinary precision, the quantum sensor could eliminate the need for a two-satellite system or provide even greater accuracy if deployed on a second satellite in a complementary orbit, said Lee Feinberg, a Goddard optics expert also involved in the effort.

"With this new technology, we can measure the changes of Earth's gravity that come from melting ice caps, droughts, and draining underground water supplies, greatly improving on the pioneering GRACE mission," said John Mather, a Goddard scientist and winner of the Nobel Prize in Physics in 2006 for his work on NASA's Cosmic Background Explorer that helped cement the big-bang theory of the universe.

"The sensitivity of quantum sensors improves as they observe individual atoms for longer measurement times; however, Earth's gravity limits the measurement durations for ground-based compact sensors," said Brent Young, AOSense president.

The Goddard-AOSense team built this terrestrial proof-of-concept gravity gradiometer.

"Operating in a microgravity environment will allow our sensors to achieve their ultimate performance. They could potentially observe one-centimeter changes in the height of Earth's water table with 100-kilometer (about 62 miles) spatial resolution."

The instrument, however, could be used to answer other scientific questions.

"We can measure the interior structure of planets, moons, asteroids, and comets when we send probes to visit them. The technology is so powerful that it can even extend the Nobel-winning measurements of gravitational waves from distant black holes, observing at a new frequency range," Mather said, referring to the confirmation in 2015 of cosmic gravitational waves — literally, ripples in the fabric of space-time that radiate out in all directions, much like what happens when a stone is thrown into a pond. Since that initial confirmation, the Laser Interferometer Gravitational Wave Observatory (LIGO) and the European Virgo detectors have detected other events. ❖

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NASA's GEDI Now Gathering Forest Data; Innovative Instrument Serves as Poster Child for R&D

Photo Credit: Desiree Stover/NASA

Optical Alignment Lead Engineer Bente Eegholm's reflection can be seen in the primary mirror of GEDI's receiver telescope. The photo was taken at a Goddard clean room before the payload was shipped to Kennedy Space Center for launch.

Instrument scientist Bryan Blair had just finished writing the flight software for the Goddard-developed Mars Orbiter Laser Altimeter, or MOLA, when he was invited in 1991 to fly a lidar instrument aboard a P-3 research aircraft to test new lidar techniques over the ice sheets in Greenland. En route, he gathered measurements of forested areas in New York. What he discovered in the data stunned him, resulting in a 27-year quest to build a spaceborne lidar for measuring forests.

That instrument — the Global Ecosystems Dynamics Investigation, or GEDI — is now collecting data as a payload attached to the Japanese Experiment Module, the largest research facility on the International Space Station.

"We were shooting lasers over forests and what we saw were crazy, complicated results in the signals that came back possibly indicating the structure of the forests below," recalled Blair, who now serves as the GEDI deputy principal investigator.

The aircraft flight and discovery got him thinking: could light detection and ranging, or lidar — the technique that scientists used to map the barren Martian topography with MOLA — be equally effective at mapping forests? Relying exclusively on research-and-development funds, he advanced an innovative idea into the first-ever mission dedicated to providing three-dimensional views of forests and details about the role of forests in the carbon cycle.

"GEDI's development is a testament to the value of research and development, which often matures 'crazy ideas' into instruments. It also underscores the importance of conceiving an idea, building a prototype, testing the instrument, and, as in GEDI's case, building an aircraft-type instrument first to iron out the measurement technique and needed technologies," said Goddard Chief Technologist Peter Hughes. "GEDI is a poster child for what can happen when NASA invests in good ideas."

Innovative Technologies Enable GEDI

Led by University of Maryland professor Ralph Dubayah, GEDI, pronounced Jedi, as in the Star Wars fame, carries out its job with several innovative technologies. Central to GEDI's capabilities is its trio of specialized lasers that send laser beams toward Earth where they penetrate forests and ricochet off everything they hit, which can be leaves atop a dense canopy, protruding branches, and, eventually, the ground from which the forest emerges. Its onboard telescope then receives the reflected signals tagging the time they take to return.

However, GEDI, which NASA's Earth Venture program selected for development four years ago, does more. Unlike many other lidar instruments flown in

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space, GEDI employs the so-called waveform-based measurement technique that analyzes the shape of the returned light, not just the time it took to return. The waveform reveals the distribution of surfaces above the terrain, making it especially useful for measuring the density of trees and vegetation, and even the structure of leaves and branches within a forest's canopy.

The 1,160-pound GEDI also sits on a gimbal, and therefore, is actively pointed to specific ground tracks on the Earth below. To give it an even wider view of the surface, GEDI uses sophisticated optics that divide the three laser beams into eight ground tracks — two of the lasers generate two ground tracks each, and the third generates four. Together, these technologies allow GEDI to sample all land between 51.6 degrees north latitude and 51.6 degrees south latitude covering temperate and tropical forests.

"Without the pointing system, it would have taken three times as long to complete the coverage we need," Blair explained.

LVIS: The Essential Pathfinder

Blair stresses that GEDI wouldn't have been possible without its predecessor, an aircraft-based instrument called Land, Vegetation and Ice Sensor, or LVIS, which Blair began flying in the late 1990s, just a few years after he conceived the instrument concept. Since then, LVIS has become something of a mainstay for more localized measurements. In addition to mapping forests, LVIS has measured ice sheets.

LVIS not only provided never-before-obtained data about forest canopies, it created a community of data users familiar with the measurement technique and its usefulness — a community that will make use of GEDI's more global measurements over the coming months, Blair said. "Without this already-established community of users, it would have been harder trying to get the mission funded," he said.

"We pioneered this mission at Goddard," Blair added. "It's a nice story for Goddard. We couldn't have accomplished this without support from Goddard's R&D programs over the years. This is a homegrown instrument based on a homegrown measurement technique." ❖

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SNoOPI: A Flying Ace for Soil Moisture and Snow Measurements

Work has begun on a new CubeSat mission that will demonstrate for the first time a new, highly promising technique for measuring soil moisture from space — data important for early flood and drought warnings as well as crop-yield forecasts.

The technology-demonstration mission, SigNals of Opportunity: P-band Investigation, will validate a remote-sensing technique called signals of opportunity. Although scientists have proven the concept in ground-based campaigns, SNoOPI, as the mission is also known, will be the first on-orbit demonstration when it's deployed into a low-Earth orbit in 2021.

Ultimately, scientists want to fly a constellation of tiny satellites, all employing the same technique, to determine the amount of water stored in snowpack and that which is present in soil in the root zone — measurements not possible with current space-based technology.

To gather this data, SNoOPI will operate a little differently than other missions. Instead of generating and transmitting its own radio signals toward Earth and then analyzing the returned signal, it will take advantage of already-available telecommunications signals.

Specifically, SNoOPI will retrieve the P-band radio signal, which is sensitive to moisture levels, in transmissions from a telecommunications satellite orbiting 22,000 miles above Earth's surface. As with visible light, these signals hit Earth, interact with the environment, and literally bounce back into space where SNoOPI's sole instrument lies in wait to collect the P-band frequency. By analyzing the returned signals, scientists can derive moisture readings.

Ideal Application

For the SNoOPI mission, the signals-of-opportunity technique is ideal, said Jeffrey Piepmeier, one of several Goddard engineers involved in the mission led by Purdue University Professor James Garrison and funded by NASA's In-Space Validation of Earth Science Technologies, or InVEST, program.

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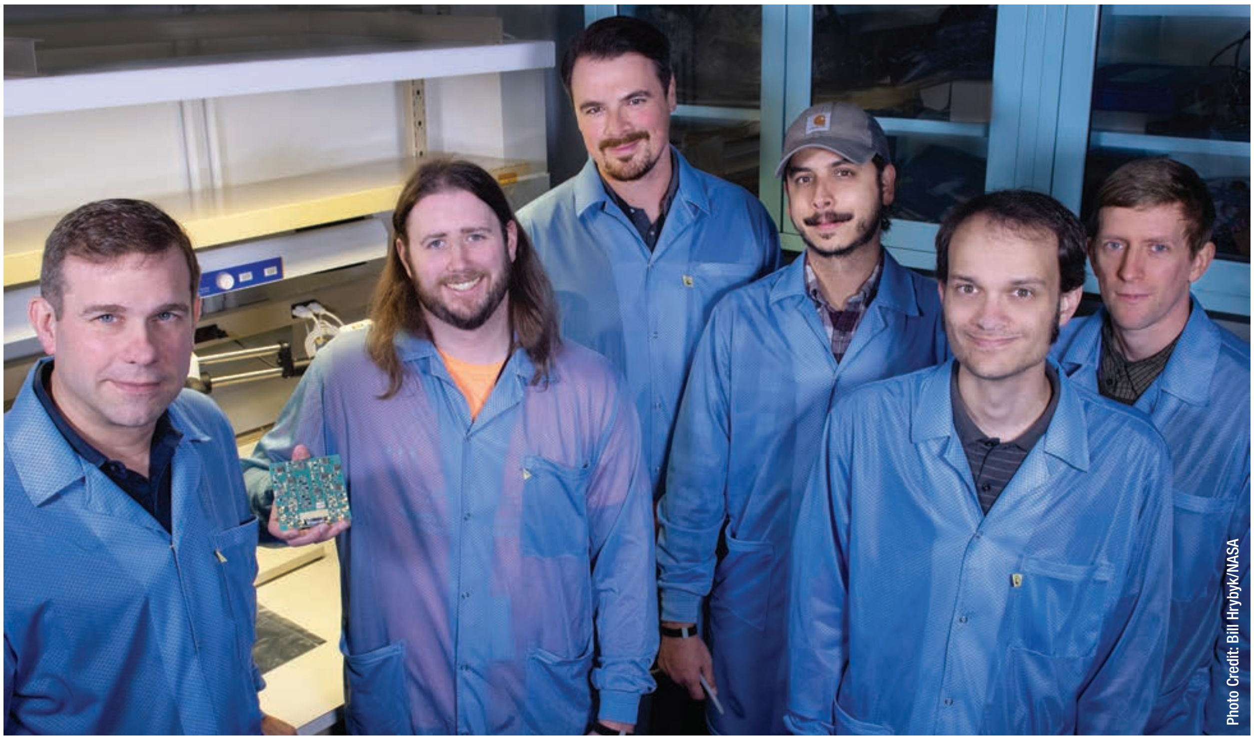

Several Goddard technologists are involved in a new CubeSat technology-demonstration mission called SNoOPI, which employs a novel remote-sensing technique for measuring soil-moisture levels. From left to right: Jeffrey Piepmeier, Chase Kielbasa, who is holding a first-generation prototype circuit board for the SNoOPI instrument, Joseph Knuble, Manuel Vega, Michael Coon, and Derek Hudson.

NASA's Soil Moisture Active Passive, or SMAP, mission is currently gathering moisture data. However, instead of P-band, it employs another radio frequency — the higher-frequency L-band — to map the amount of water in the top two inches of soil everywhere on Earth's surface. However, SMAP can't gather moisture readings at the root level. It also encounters difficulties when measuring soil moisture in forested and mountainous areas.

Lower frequencies, like the P-band, can travel four times deeper into the soil or snowpack, thereby overcoming the L-band limitation. But P-band has its own shortcomings. Because traditional P-band instruments are prone to radio interference caused by signal spillover from neighboring spectrum users, they require a large antenna to actively transmit and receive signals to obtain sufficient spatial resolution.

Because SNoOPI reuses already-existing telecommunications signals, it doesn't need a transmitter. Furthermore, the telecommunications signal SNoOPI ultimately captures after it bounces back into space is extremely powerful, eliminating the need for a large antenna, Piepmeier explained.

"The signal efficiency makes this technique very cost effective," Piepmeier said. "Because we eliminate the need for a large antenna, it enables the technique's use on a CubeSat, which can be the size of a loaf of bread."

Goddard and the Jet Propulsion Laboratory are building SNoOPI's instrument and an external vendor will provide the CubeSat bus. Garrison, who conceived the P-band signals-of-opportunity technique, is managing the overall mission-development effort.

Should the technique prove effective in space, the team believes NASA could fly as many as nine small satellites along a polar orbit to build root-zone maps needed by weather forecasters, water managers, farmers, and power-plant operators. ❖

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Cutting edge Goddard's Emerging Technologies

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