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Cutting edge

Goddard's Emerging Technologies

Galactic GPS: NASA Plants the Flag

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NASA Plants the Flag on Galactic GPS

Team Demonstrates X-ray Navigation for the First Time

In a technology first, a team of Goddard engineers has demonstrated fully autonomous X-ray navigation in space — a capability that could revolutionize NASA's ability in the future to pilot spacecraft to the far reaches of the solar system and beyond.

> *"We planted the flag on this one. Many people were pursuing this technology and we were the first to demonstrate it. We were the first to do it fully autonomously and in real-time in space."*
>
> ***– Jason Mitchell, SEXTANT Project Manager***

The demonstration, which the team carried out with an experiment called Station Explorer for X-ray Timing and Navigation Technology, or SEXTANT, showed that millisecond pulsars could be used to accurately determine the location of an object moving at thousands of miles per hour in space — similar to how the Global Positioning System, widely known as GPS, provides positioning, navigation, and timing services to users on Earth with its constellation of 24 operating satellites.

"We planted the flag on this one. Many people were pursuing this technology and we were the first to demonstrate it," said SEXTANT Project Manager Jason Mitchell, referring to teams in China and Europe that also had launched or had begun the development of X-ray navigation, or XNAV, systems. "We were the first to do it fully autonomously and in real-time in space."

This technology provides a new option for deep space navigation that could work in concert with existing spacecraft-based radio and optical systems.

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About the Cover

A Goddard team, including Jason Mitchell (right) and Luke Winternitz (left), have demonstrated fully autonomous X-ray navigation in space — a world first. The capability could revolutionize NASA's ability in the future to pilot spacecraft to the far reaches of the solar system and beyond. The experiment, called SEXTANT, showed that millisecond pulsars could be used to determine the location of an object moving at thousands of miles per hour.

Photo Credit: Bill Hrybyk/NASA

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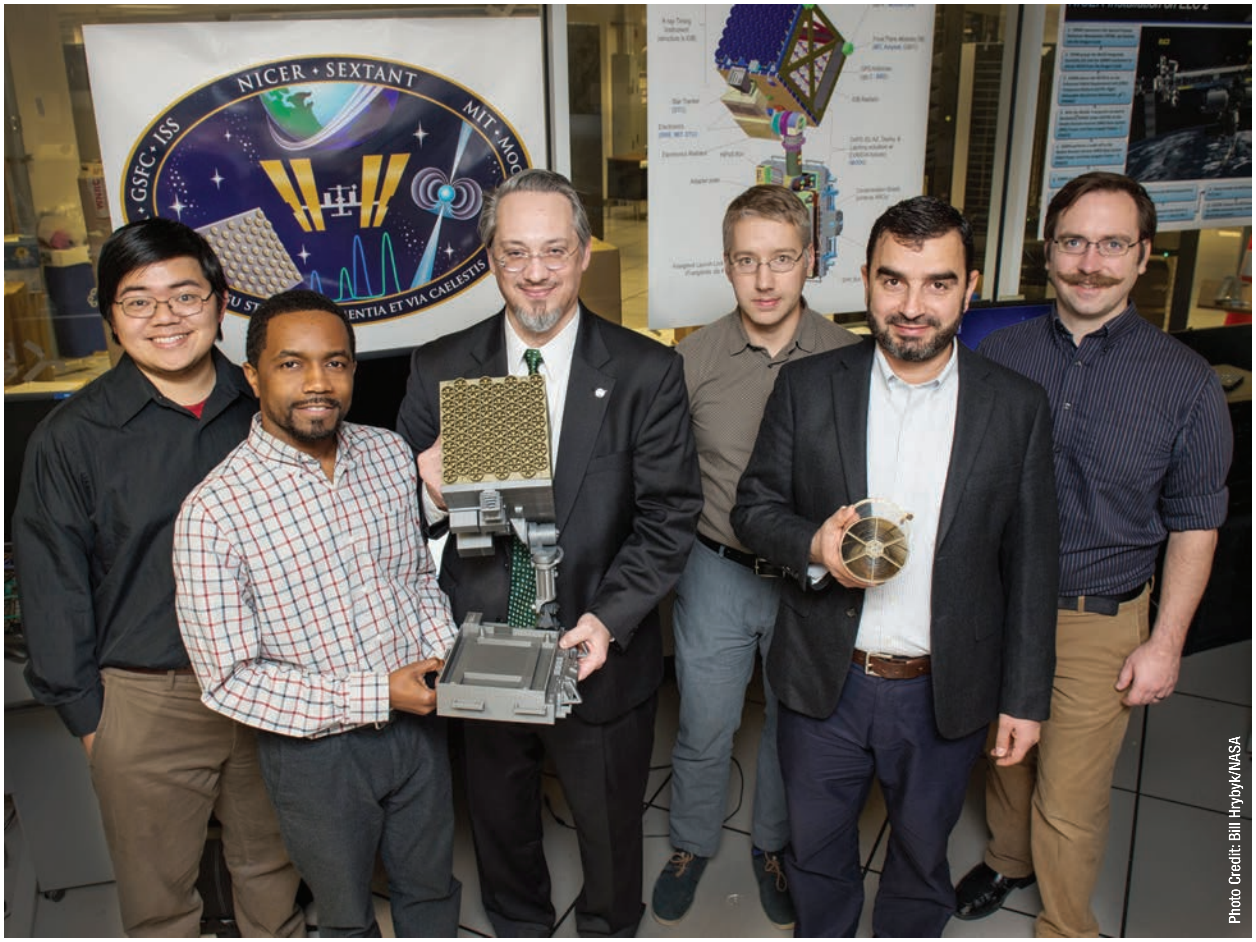

Photo Credit: Bill Hrybyk/NASA

The team that demonstrated fully autonomous X-ray navigation in space — a capability that could revolutionize NASA's ability in the future to pilot spacecraft to the far reaches of the solar system and beyond — include from left to right: Wayne Yu, Sean Semper, Jason Mitchell, Luke Winternitz, Munther Hassouneh, and Sam Price.

Although it could take a few years to mature an XNAV system practical for use on deep-space missions, the fact that NASA engineers proved that it could be done bodes well for future interplanetary space travel. If equipped with such a system, spacecraft could autonomously determine their locations outside the currently used Earth-based global navigation networks because pulsars are accessible in virtually every conceivable fight regime, from low-Earth to deepest space.

Exploiting NICER Telescopes

The SEXTANT technology demonstration, which NASA's Space Technology Mission Directorate had funded under its Game Changing Program, took advantage of the 52 X-ray telescopes and silicon-drift detectors that make up NASA's Neutron-star Interior Composition Explorer, or NICER. Since its successful deployment as an external attached payload on the International Space Station in June, it has trained its optics on some of the most unusual objects in the universe (*CuttingEdge*, Spring 2017, Page 7).

This washing machine-sized observatory currently is studying neutron stars and their rapidly pulsating cohort, called pulsars. Although these stellar oddities emit radiation across the electromagnetic spectrum, observing in the X-ray band offers the greatest insights into these unusual, incredibly dense celestial objects, which, if compressed any further, would collapse completely into black holes. Just one teaspoonful of neutron-star matter would weigh a billion tons on Earth.

Although NICER is studying all types of neutron stars, the SEXTANT experiment is focused on observations of pulsars. Radiation emanating from their powerful magnetic fields is swept around much like a lighthouse. The narrow beams are seen as flashes of light when they sweep across our line of sight. With these predictable pulsations, pulsars

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NICER Observes 174 Celestial Targets Since Its Deployment

The dual-purpose Neutron star Interior Composition Explorer, or NICER — the payload that hosted an experiment demonstrating autonomous, real-time X-ray navigation, or XNAV, in space (see related story, page 2) — has so far observed 174 celestial targets since its successful deployment on the International Space Station in 2017.

"We're doing very cool science and using the space station as a platform to execute that science, which in turn enables XNAV," said Keith Gendreau, the NICER principal investigator at Goddard.

NICER is a dual-purpose payload. The NICER team primarily designed the mission to study neutron stars and their pulsating cohorts, pulsars. However, its mission also enabled the team to develop algorithms and other hardware to demonstrate XNAV in space.

Since its deployment, the payload has observed primarily neutron stars and is on track to derive the interior composition of these ultra-dense, yet stable, objects. The team, which made NICER data available in mid-January 2018, hopes the mission will discover more pulsars that will be suitable for future navigation demonstrations.

"One of NICER's goals is to find new pulsars," said the mission's science lead, Zaven Arzoumanian. "With higher sensitivity than past X-ray timing missions, we can detect new neutron stars both for our science objectives and as 'beacon' pulsars for future navigation applications." ❖

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Photo Credit: Bill Hrybyk/NASA

Principal Investigator Keith Gendreau — the scientist who advanced the dual-purpose NICER/SEXTANT mission — works at the mission's operations center at Goddard.

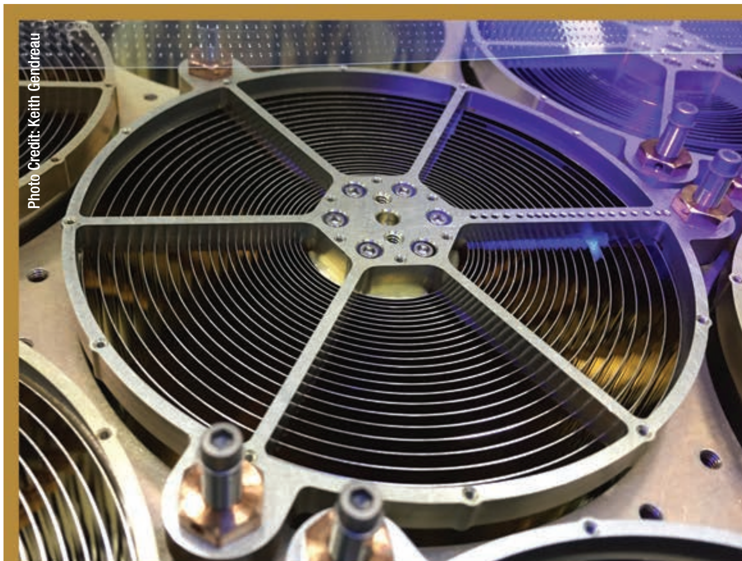

Photo Credit: Keith Gendreau

This is a closeup of one of the 52 X-ray mirror assemblies on NICER. These mirror assemblies concentrate X-rays onto silicon detectors to gather data that probes the interior makeup of neutron stars, including those that appear to flash regularly, called pulsars.

Optics Lead Takashi Okajima adjusts the orientation of NICER/SEXTANT's X-ray optic "concentrator" made up of 52 X-ray mirror assemblies. The SEXTANT experiment used these optics to gather enough data to demonstrate X-ray navigation in space using the predictable pulsations of four pulsar stars.

Photo Credit: NASA

can provide high-precision timing information just like the atomic-clock signals supplied through the GPS system.

Veteran's Day Demonstration

In the SEXTANT demonstration that occurred over the Veteran's Day holiday in 2017, the SEXTANT team selected four millisecond pulsar targets — J0218+4232, B1821-24, J0030+0451, and J0437-4715 — and directed NICER to orient itself so that it could detect X-rays within their sweeping beams of light. The millisecond pulsars used by SEXTANT are so stable that their pulse arrival times can be predicted to accuracies of better than a microsecond for years into the future.

During the two-day experiment, the payload generated 78 measurements to get timing data, which the SEXTANT experiment fed into its specially developed 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. The team compared that

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Scientists operate the NICER mission and the X-ray navigation experiment, SEXTANT, from the operations center at Goddard.

solution against location data gathered by the GPS receiver aboard NICER.

“For the onboard measurements to be meaningful, we needed to develop a model that predicted the arrival times using ground-based observations provided by our collaborators at radio telescopes around the world,” said Paul Ray, a SEXTANT co-investigator from the U. S. Naval Research Laboratory. “The difference between the measurement and the model prediction is what gives us our navigation information.”

“This was much faster than the two weeks we allotted for the experiment. We had indications that our system would work, but the weekend experiment finally demonstrated the system’s ability to work autonomously.”

– Luke Winternitz, SEXTANT System Architect

The goal was to demonstrate that the system could locate NICER within a 10-mile radius as the space station sped around the Earth at slightly more than 17,000 miles per hour. Within eight hours of starting the experiment on November 9, the system converged on a location within the targeted range of 10 miles and remained well below that threshold for the rest of the experiment, Mitchell said. In fact, “a good portion” of the data showed positions that were accurate to within three miles.

“This was much faster than the two weeks we allotted for the experiment,” said SEXTANT System Architect Luke Winternitz. “We had indications that our system would work, but the weekend experiment finally demonstrated the system’s ability to work autonomously.”

Although the ubiquitously used GPS system is accurate to within a few feet for Earthbound users, this level of accuracy typically is not necessary when navigating to the far reaches of the solar system where distances between objects measure in the millions of miles. However, “in deep space, we hope to reach accuracies in the hundreds of feet,” Mitchell said.

“Having watched the development of this technology over the years, I’m confident that this team will reach this ambitious goal,” said Goddard Chief Technologist Peter Hughes, who manages Goddard’s Internal Research and Development, or IRAD, program. “The IRAD program supported NICER technologies long before the mission became a NASA Explorer Mission of Opportunity. It’s gratifying to see how successful the technology is proving to be in our quest to develop technologies for exploring deeper into space.”

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This illustration shows the NICER mission at work aboard the International Space Station.

Next Steps and the Future

Now that the team has demonstrated the system, Winternitz said the team will focus on updating and fine-tuning both flight and ground software in preparation for a second experiment later in 2018. The ultimate goal, which may take years to realize, would be to develop detectors and other hardware to make pulsar-based navigation readily available on future spacecraft.

If an interplanetary mission to the moons of Jupiter or Saturn were equipped with such a navigational device, for example, it would be able to calculate its location autonomously, for long periods of time without communicating with Earth. Mitchell said that GPS is not an option for these far-flung missions because its signal weakens quickly as one travels beyond the GPS satellite network around Earth.

To advance the technology for operational use, teams will focus on reducing the size, weight, and power requirements and improving the sensitivity of the instruments. The SEXTANT team also is discussing the possible application of X-ray navigation to support human spaceflight, Mitchell added.

"This successful demonstration firmly establishes the viability of X-ray pulsar navigation as a new autonomous navigation capability. We have shown that this technology can enable and enhance deep-space exploration anywhere within the solar system and beyond," Mitchell said. "It is an awesome technology first." ❖

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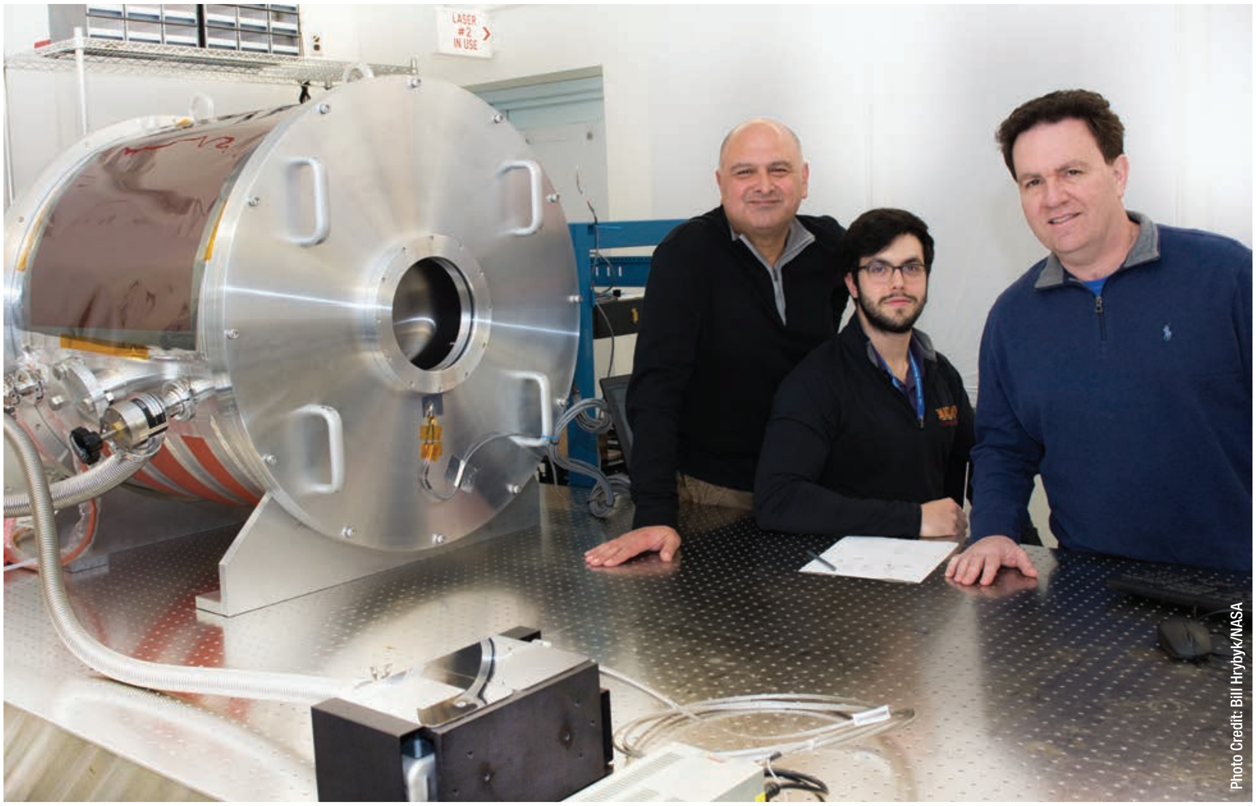
Poised to Topple a Planet-Finding Barrier

Goddard Optics Experts Measure to Picometer Accuracy — a NASA First



Goddard optics experts Babak Saif (left) and Lee Feinberg (right), with help from engineer Eli Griff-McMahon (center), an employee of Genesis, have created an ultra-stable thermal-vacuum system that they will use to make picometer-level measurements.

Goddard optics experts are well on the way to toppling a barrier that has thwarted scientists from achieving a long-held ambition: building an ultra-stable telescope that locates and images dozens of Earth-like planets beyond the solar system and then scrutinizes their atmospheres for signs of life.

Babak Saif and Lee Feinberg, who collaborated with Perry Greenfield at the Space Telescope Science Institute in Baltimore, have shown for the first time that they can dynamically detect subatomic- or picometer-sized distortions — changes that are far smaller than an atom — across a five-foot segmented telescope mirror and its support structure. They now plan to use a next-generation tool and thermal-test chamber to further refine their measurements.

The measurement feat is good news to scientists studying future missions for finding and characterizing extra-solar Earth-like planets that potentially could support life.

To find life, these observatories would have to gather and focus enough light to distinguish the planet's light from that of its much brighter parent star and then be able to dissect that light to discern different atmospheric chemical signatures, such as oxygen and methane. This would require a super-stable observatory whose optical components move or distort no more than 12 picometers, a measurement that is about one-tenth the size of a hydrogen atom.

To date, NASA has not built an observatory with such demanding stability requirements.

How Displacements Occur

Displacements and movement occur when materials used to build telescopes shrink or expand due to wildly fluctuating temperatures, such as those experienced when traveling from Earth to the frigidity of space, or when exposed to fierce launch forces more than six-and-a-half times the force of gravity.

Scientists say that even nearly imperceptible, atomic-sized movements would affect a future

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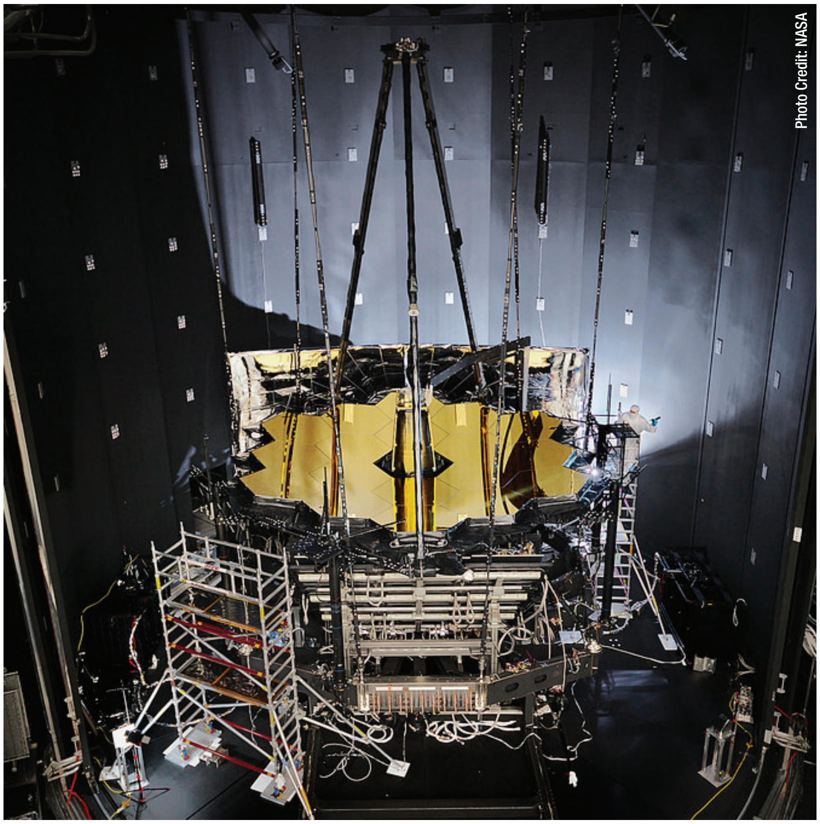
observatory's ability to gather and focus enough light to image and analyze a planet's light. Consequently, mission designers would have to design the observatory to picometer accuracies and then test it at the same level across the entire structure, not just between the telescope's reflective mirrors. Movement occurring at any particular position might not accurately reflect what's happening in other locations.

"These future missions will require an incredibly stable observatory," said Azita Valinia, Astrophysics Projects Division deputy program manager. "This is one of the highest technology tall poles that future observatories of this caliber must overcome. The team's success has shown that we are steadily whittling away at that particular obstacle."



A Goddard team used a spare, five-foot mirror segment built for the James Webb Space Telescope shown here to test techniques for measuring picometer-sized distortions in observatory optics and support structure.

The Initial Test

To carry out the test, Saif and Feinberg used the High-Speed Interferometer, or HSI — an instrument that the Arizona-based 4D Technology developed to measure nanometer-sized dynamic changes in the James Webb Space Telescope's optical components — including its 18 mirror segments, mounts, and other supporting structure — during thermal, vibration, and other types of environmental testing.

Like all interferometers, the instrument splits light and then recombines it to measure tiny changes, including motion. The HSI can quickly measure dynamic changes across the mirror and other structural components, giving scientists insights into what is happening across the telescope, not just in one particular spot.

Even though the HSI was designed to measure nanometer or molecule-sized distortions — which was the design standard for Webb — the team wanted to see if it could use the same instrument, coupled with specially developed algorithms, to detect even smaller changes across support hardware and the surface of a spare, five-foot mirror segment built for the Webb Observatory.

The test proved it could, measuring dynamic movement as small as 25 picometers — about twice the desired target, Saif said.

Next Steps

However, Goddard and 4D Technology have designed a new high-speed instrument, called a speckle interferometer, that allows measurements of both reflective and diffuse surfaces at picometer accuracies. 4D Technology has built the instrument and the Goddard team has begun initial characterization of its performance in a new thermal-vacuum test chamber that controls internal temperatures to a frosty 1-millikelvin.

Saif and Feinberg plan to place test items inside the chamber to see if they can achieve the 12-picometer target accuracy. They also are evaluating other technologies to relax the requirements so that mission designers wouldn't have to work in the picometer regime, Feinberg said.

"I think we've made a lot of progress. We're getting there," Saif said. "What we need to achieve is a measurement — 12 picometers — which is where we want to be." ❖

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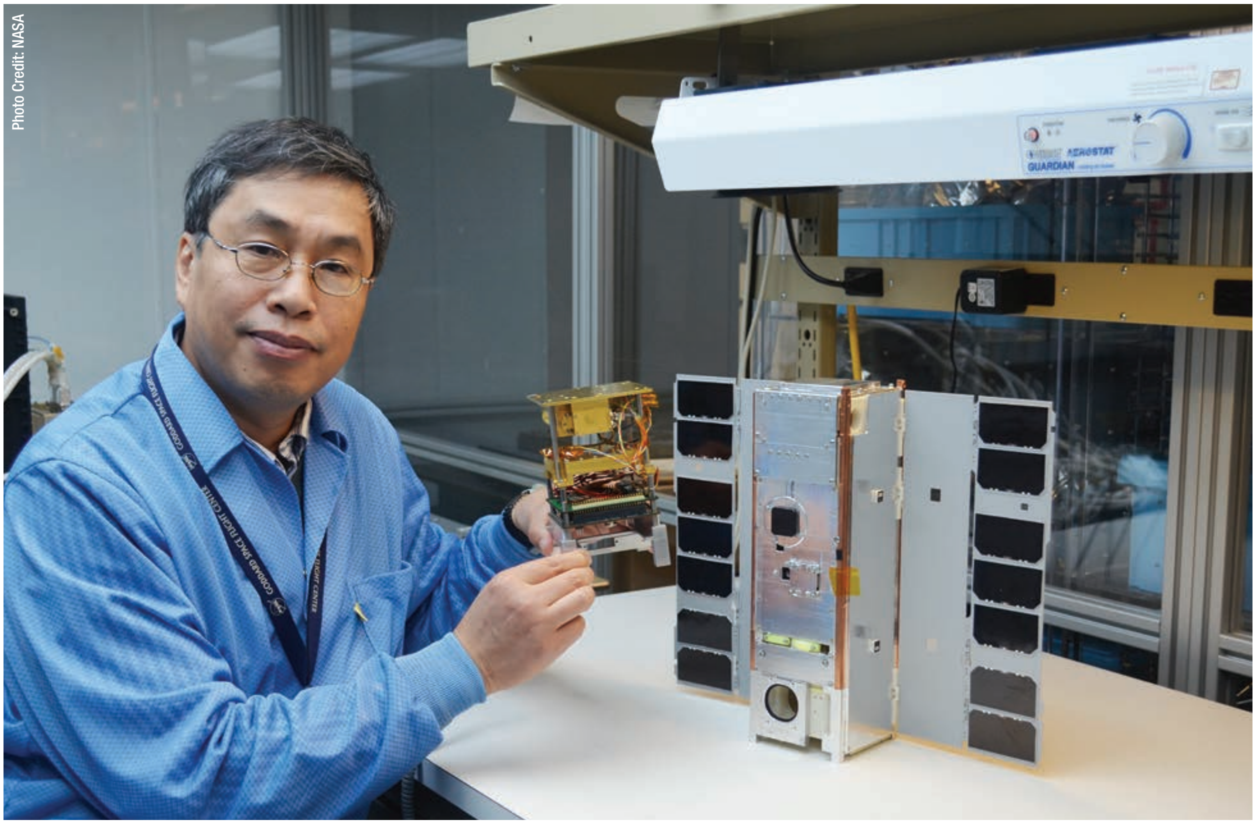
Bread Loaf-Sized Spacecraft Exceeds Expectations — Produces First 883-Gigahertz Global Ice-Cloud Map



IceCube Principal Investigator Dong Wu set out to demonstrate a commercial 883-Gigahertz radiometer in space, but ended up getting much more: the world's first ice-cloud map in that frequency. Here he is pictured holding the instrument.

A bread loaf-sized satellite originally developed to demonstrate a measurement technique never before tried in space has exceeded expectations and, in fact, has produced the world's first map of the global distribution of atmospheric ice in the 883-Gigahertz band, an important frequency in submillimeter wavelengths for studying cloud ice and its effect on Earth's climate.

IceCube — the diminutive spacecraft that began operations in June, one month after its deployment from the International Space Station — has demonstrated in space a commercial 883-Gigahertz radiometer developed by Virginia Diodes Inc., or VDI, of Charlottesville, Virginia, under a NASA Small Business Innovative Research contract.

Goddard scientists pioneered the use of submillimeter wavelength bands, which fall between the microwave and infrared on the electromagnetic spectrum, to sense ice clouds. However, until IceCube, these instruments had flown only aboard high-altitude research aircraft. This meant that scientists could gather data only in areas over which the aircraft flew.

"With IceCube, scientists now have a working submillimeter radiometer system in space at a commercial price," said IceCube Principal Investigator Dong Wu. "More importantly, it provides a global view on Earth's cloud-ice distribution."

Sensing atmospheric cloud ice requires that scientists deploy instruments tuned to a broad range of frequency bands. However, it's particularly important to fly submillimeter sensors. This wavelength fills a significant data gap in the middle and upper troposphere where ice clouds are often too opaque for infrared and visible sensors to penetrate. It also reveals data about the tiniest ice particles that can't be detected clearly in other microwave bands.

The Technical Challenge

"IceCube's map is a first of its kind and bodes well for future space-based observations of global ice

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clouds using submillimeter-wave technology, said Wu, whose team built the spacecraft using funding from NASA's Earth Science Technology Office's In-Space Validation of Earth Science Technologies program and NASA's Science Mission Directorate. The team's challenge was making sure the commercial receiver was sensitive enough to detect and measure atmospheric cloud ice using as little power as possible.

Ultimately, the agency wants to infuse this type of receiver into an ice-cloud imaging radiometer for NASA's proposed Aerosol-Cloud-Ecosystems, or ACE, mission. Recommended by the National Research Council, ACE would assess on a daily basis the global distribution of ice clouds, which affect the Earth's emission of infrared energy into space and its reflection and absorption of the Sun's energy over broad areas. Before IceCube, this value was highly uncertain.

The bread loaf-sized IceCube was deployed from the International Space Station in May. One month later, it began science operations gathering global data about atmospheric ice clouds in the submillimeter wavelengths.

"It speaks volumes that our scientists are doing science with a mission that primarily was supposed to demonstrate technology," said Jared Lucey, one of IceCube's instrument engineers. Lucey, along with a handful of scientists and engineers at Goddard and the Wallops Flight Facility, developed IceCube in just two years with a limited budget. "We met our mission goals and now everything else is bonus."

Multiple Lessons Learned

In addition to demonstrating submillimeter-wave observations from space using a commercially available instrument and producing the ice-cloud map, the team gained important insights into how to efficiently develop a CubeSat mission, determining which systems to make redundant and which tests to forgo because of limited funds and a short schedule, said Jaime Esper, IceCube's mission systems designer and technical project manager at Goddard.

"It wasn't an easy task," said Negar Ehsan, IceCube's instrument system lead. "It was a low-budget project" that required the team to develop both an engineering test unit and a flight model in a relatively short period of time. In spite of the budget and schedule limitations, however, the team delivered the VDI-provided instrument on time and budget, with money to spare. "We demonstrated for the first time 883-Gigahertz observations in space and proved that the VDI-provided system works appropriately," she said. "It was rewarding."

To keep down costs, the team used commercial off-the-shelf components, including, of course, VDI's radiometer. The components came from multiple commercial providers and didn't always work together harmoniously, requiring engineering rework on the part of team members. The team not only integrated the radiometer to the spacecraft, but also built spacecraft ground-support systems and conducted thermal-vacuum, vibration, and antenna testing at Goddard's Greenbelt campus and Wallops' facilities in Virginia.

"IceCube isn't perfect," Wu conceded, referring to noise or slight errors in the radiometer's data. "However, we can make a scientifically useful measurement. We came away with a lot of lessons learned from this CubeSat project, and next time engineers can build it much more quickly. But under this program, we had to complete the project within a limited budget and schedule, and therefore, we had to take and balance the risks."

"This is a different mission model for NASA," Wu continued. "Our principal goal was to show that this small mission could be done at NASA. The question was, could we get useful science and advance space technology with a low-cost CubeSat developed under an effective government-commercial partnership? I believe the answer is yes." ❖

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High-Demand Crosscutting Technology Finds Another Home on BurstCube

Recently Awarded CubeSat Mission to Search for Electromagnetic Counterparts of Gravitational Waves

Georgia de Nolfo — a heliophysicist who has created a highly compact detector technology applicable to all types of cross-disciplinary scientific investigations performed aboard pint-sized spacecraft — is on a roll.

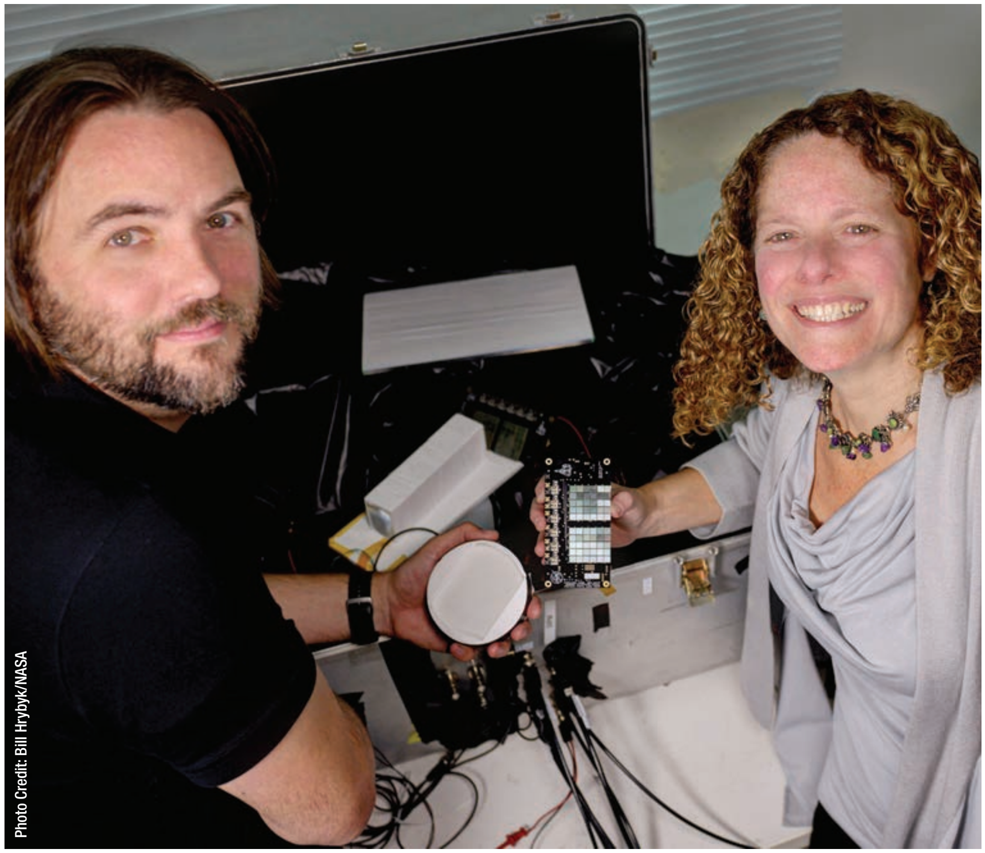

Photo Credit: Bill Hrybyk/NASA

Principal Investigator Jeremy Perkins and his co-investigator, Georgia de Nolfo, recently won funding to build a new CubeSat mission, called BurstCube. Respectively, Perkins and de Nolfo hold a crystal, or scintillator, and a silicon photomultiplier array that will be used to detect and localize gamma-ray bursts for gravitational-wave science.

She and her collaborator, Goddard astrophysicist Jeremy Perkins, recently won funding from NASA's Astrophysics Research and Analysis Program to develop a CubeSat mission called BurstCube. This mission, which will carry her compact sensor technology, will detect and localize gamma-ray bursts caused by the collapse of massive stars and mergers of orbiting neutron stars. It also will detect solar flares and other high-energy transients once it's deployed into a low-Earth orbit sometime in the early 2020s.

The cataclysmic deaths of massive stars and mergers of neutron stars are of special interest to scientists because they produce 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 the Laser Interferometer Gravitational Wave Observatory, or LIGO, confirmed their existence in 2015 with a binary black-hole merger, LIGO and the European Virgo detectors have detected other events, including the first-ever detection of gravitational waves from the merger of two neutron stars announced in October 2017. Less than two seconds after LIGO detected the waves washing over Earth's space-time, NASA's Fermi Gamma-ray Space Telescope detected a weak burst of high-energy light — the first burst to be unambiguously connected to a gravitational-wave source.

These detections have opened a new window on the universe, giving scientists a more complete view of these events that complements what they already have learned through more traditional observational techniques, which rely on detecting electromagnetic radiation light — in all its forms.

Complementary Capability

Perkins and de Nolfo see BurstCube as a companion to Fermi in this search for gravitational-wave

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sources. Though not as capable as the much larger, Gamma-ray Burst Monitor, or GBM, on Fermi, BurstCube will increase coverage of the sky. Fermi-GBM observes the entire sky not blocked by the Earth. "But what happens if an event occurs and Fermi is on the other side of Earth, which is blocking its view," Perkins said. "Fermi won't see the gamma-ray burst."

BurstCube, which is expected to launch around the time additional ground-based LIGO-type observatories begin operations, will assist in detecting these fleeting, hard-to-capture high-energy photons and help determine where they originated in the universe. In addition to quickly reporting their locations to the ground so that other telescopes can find the event in other wavelengths and home in on its host galaxy, BurstCube's other job is to study the sources themselves.

Image Credit: NASA Goddard Space Flight Center/CI Lab

Scientists detected light tied to a gravitational-wave event, thanks to two merging neutron stars in the galaxy NGC 4993, located about 130 million light-years from Earth in the constellation Hydra. This illustration shows the hot, dense, expanding cloud of debris stripped from these merging stars just before they collided. A new CubeSat mission would help locate these mergers.

BurstCube will use the same detector technology as Fermi's GBM; however, with important differences.

Under the concept de Nolfo has advanced through Goddard's Internal Research and Development program funding, the team will position four blocks of cesium-iodide crystals, operating as scintillators, in different orientations within the spacecraft. When an incoming gamma-ray strikes one of the crystals, it will absorb the energy and luminesce, converting that energy into optical light.

Four arrays of silicon photomultipliers and their associated read-out devices each sit behind the four crystals. The photomultipliers convert the light into an electrical pulse and then amplify this signal by creating an avalanche of electrons, much like how a snowball gets bigger as it rolls down a hill. This multiplying effect makes the detector far more sensitive to faint and fleeting gamma rays.

Unlike the photomultipliers on Fermi's GBM, which are bulky and resemble old-fashioned television tubes, de Nolfo's devices are made of silicon, a semiconductor material. "Compared with more conventional photomultiplier tubes, silicon photomultipliers significantly reduce mass, volume, power, and cost," Perkins said. "The combination of the crystals and new readout devices makes it possible to consider a compact, low-power instrument that is readily deployable on a CubeSat platform."

In another success for Goddard technology, the BurstCube team also has baselined the Dellingr CubeSat bus that a small team of center scientists and engineers developed to show that CubeSat platforms could be more reliable and capable of gathering highly robust scientific data.

Other CubeSat Applications

BurstCube isn't the only small mission to benefit from de Nolfo's work. She currently is testing the final designs of large-area photomultiplier arrays for a National Science Foundation-funded CubeSat called TRYAD, now being built by the University of Alabama-Huntsville and Auburn University. This CubeSat mission involves two identically equipped platforms that measure terrestrial gamma-ray flashes occurring in thunderstorms.

She and her collaborator at the University of New Hampshire are completing a miniature neutron spectrometer also based on the scintillator/silicon photomultiplier technology. The instrument will fly aboard the Ionospheric Neutron Content Analyzer, or INCA, now being built by New Mexico State University-Las Cruces. INCA will study the latitude and time dependencies of the neutron spectrum in low-Earth orbit. The measurements will improve current space-weather models and help mitigate threats to space and airborne assets.

"This is high-demand technology," de Nolfo said. "There are applications everywhere." ❖

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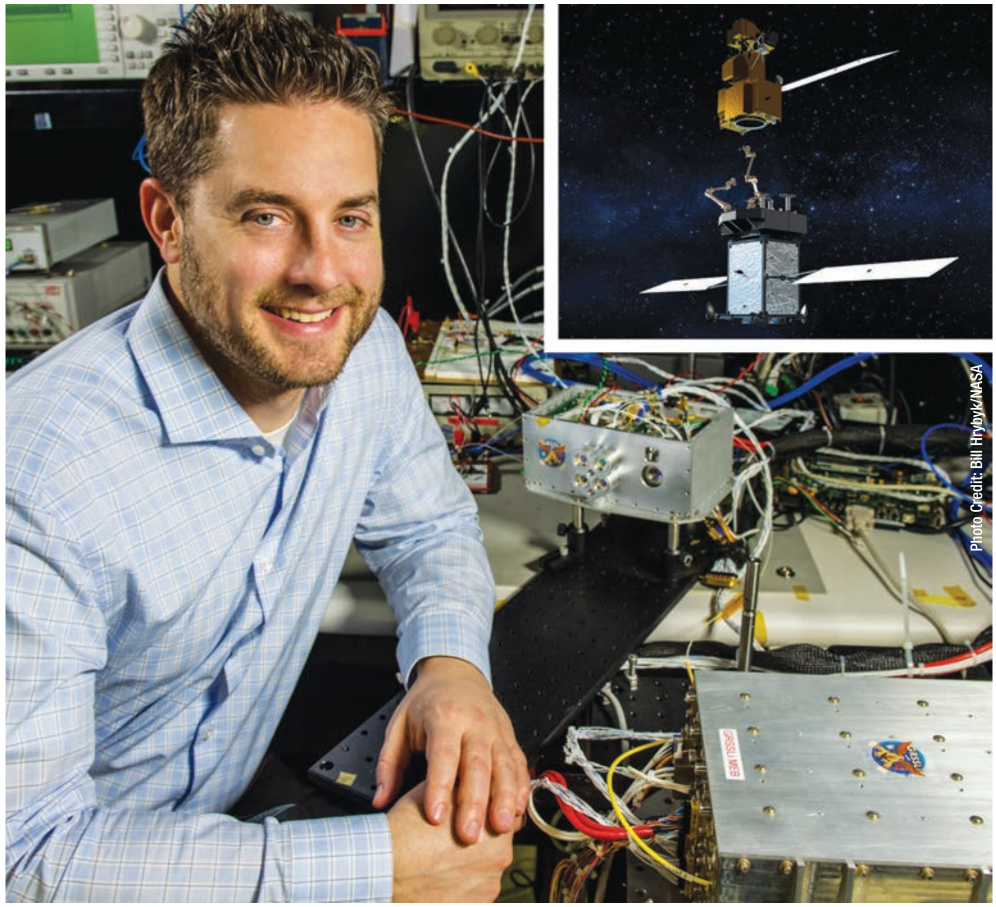
The Self-Driving Servicer

Full-Up Kodiak System Now Baselined for NASA's Restore-L Satellite-Servicing Demonstration



NASA's Satellite Servicing Projects Division has baselined Kodiak, formerly called the Goddard Reconfigurable Solid-State Scanning Lidar, also known as GRSSLi, for its Restore-L mission. Kodiak is pictured here with its creator, Nat Gill. INSET Image: This artist's rendition shows the Restore-L servicer spacecraft robotically repairing a satellite. (Image Credit: NASA)

One test changed the fortunes of an advanced 3-D imaging lidar system now baselined for NASA's Restore-L project that will demonstrate an autonomous satellite-servicing capability.

Officials with NASA's Satellite Servicing Projects Division, have officially baselined the Kodiak system — formerly known as the Goddard Reconfigurable Solid-state Scanning Lidar, or GRSSLi — to provide real-time images and distance-ranging information during Restore-L. This project will demonstrate how a specially equipped robotic servicer spacecraft can extend a satellite's lifespan — even one not originally designed for on-orbit servicing.

During the demonstration, the Restore-L servicer will use its relative navigation technologies — of which the Kodiak system now is a part — to essentially drive itself to its destination, much like a self-driving car here on terra firma. Once it locates Landsat 7, it will use its dexterous robotic arms and software to autonomously grasp, refuel, and relocate Landsat 7. Launched in 1999, this Earth-observing satellite was not designed for servicing or on-orbit repairs.

Good News for Technology Developers

The decision to use Kodiak is good news to Principal Investigator Nat Gill, who, along with other technologists, began developing the advanced scanning lidar system five years ago in part with Goddard Internal Research and Development program funding (CuttingEdge, Fall 2014, Page 16).

Less than a year ago, only a portion of Kodiak was being considered for use, primarily as a back-up to another system, Gill said.

This partial capability would have provided ranging measurements to guide the Restore-L robotic servicer as it approached the satellite from 1.5 miles down to five feet. To carry out this orbital dance, the system would have flashed its low-power laser light at Landsat 7 every 25 microseconds. Its onboard telescopes and detectors would have collected the returning light as it bounced off the satellite and another Goddard-developed technology — a hybrid computing platform called SpaceCube 2.0 — then would have calculated the light's time of flight to determine distance.

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Real-Time Imaging Added

Restore-L will use a second piece of the Kodiak system: its ability to provide real-time, high-resolution images as the robotic servicer approaches the target, which, itself, is moving at thousands of miles per hour.

This capability includes a micro-electro-mechanical scanner and a photodetector. With these components, the system "paints" a scene with the scanning laser and its detector senses the reflected light to create a 3-D image, with millimeter-level resolution, over a range of distances, from meters to kilometers.

A Test Made the Difference

A test changed Kodiak's fortunes, Gill explained.

During a demonstration involving the imaging portion of Kodiak and a mockup of Landsat 7, Gill and his team showed that the system's 3-D imaging capabilities, coupled with specially developed algorithms, "could do the job the Restore-L project requires," Gill said. "Now, we have the whole job for Restore-L, including the 3-D imaging."

As a result, mission controllers will be able to see Landsat 7 in high resolution as the robotic servicer approaches as well as automatically determine its location and relative orientation with one small, lightweight system, Gill said. "Because of our team's work ethic, technical skill, and belief in a crazy idea, we've succeeded in raising the cutting edge of spaceflight technology." ❖

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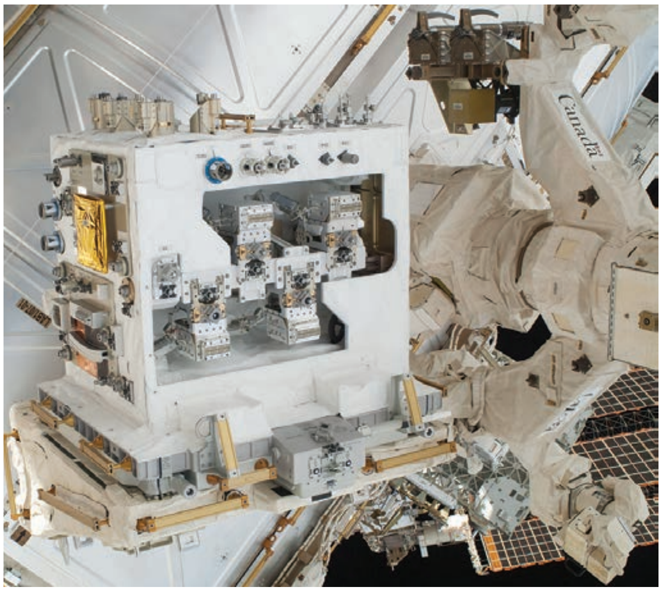
NASA to Hold Second Satellite Servicing Technology Transfer Industry Day

Up until now, we've lived in an era of "one and done" spacecraft. Barring a few notable exceptions, spacecraft launch alone, operate alone and are decommissioned alone. In an average year, several billion dollars' worth of satellites that could be refueled or repaired are retired because there is no way to service them in space.

On Jan. 30, NASA will host a satellite servicing industry day at Goddard, as part of ongoing efforts to change that paradigm. The all-day meeting will focus on technology for building in-orbit servicers and incorporating compatible servicing features and devices on future satellites.



The Robotic Refueling Mission, or RRM, module was temporarily installed on the Dextre robot's Enhanced ORU Temporary Platform on the International Space Station. RRM resided there for nearly two months before being transferred to its permanent location on an external platform fit for its robotic demonstrations.

New Era

A new era is upon us. NASA continues to develop satellite-servicing technologies to make refueling, fixing and upgrading satellites in space possible. For example, NASA's Restore-L project will demonstrate technologies for rendezvous, inspection, repair, and refueling of a client satellite in orbit. These technologies will allow fleet managers to call on robotic mechanics to diagnose, maintain and extend the lifespan of their assets (see related story, page 14).

Key to NASA's plan for making satellite servicing ubiquitous is the transfer of servicing technologies to

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Geared up and ready to go, SSPD team member and robot operator Alex Janas attaches a Robotic Refueling Mission, or RRM, tool onto the industrial robot arm before simulating an RRM servicing task.

interested U.S. companies, in tandem with development, to help jumpstart a new domestic commercial-servicing industry with a robust fleet of servicers.

"NASA recognizes the best way to create a competitive market and position the U.S. as the global leader in satellite servicing is through technology transfer," said Benjamin Reed, the deputy director of Goddard's Satellite Servicing Projects Division, or SSPD.

Access to SSPD's Updated Tech Catalog

The upcoming industry day will offer attendees access to an updated technology catalog of more than 200 items, presentations about the latest technology developments by SSPD subject-matter experts, and a tour of Goddard's Robotic Operations Center where the technologies are tested.

Attendees will have access to NASA's programmatic, technical, and operational expertise in satellite servicing, with opportunities to discuss potential public-private-partnerships. Some technologies NASA will discuss and make available include: the relative navigation system, robot arm and software, tool drive system and tools, fluid transfer system, and servicing avionics and software.

For cooperative servicing, SSPD will offer information about rendezvous/capture decal technology and the Cooperative Service Valve.

In addition to the Restore-L project, SSPD will cover two of its technology maturation projects that use the International Space Station to develop crosscutting servicing technologies — the Robotic Refueling Mission 3, or RRM3, which is developing and demonstrating technologies for cryogen and xenon transfer, and Raven, a technology demonstration of state-of-the-art relative navigation capabilities.

The first formal technology-transfer campaign took place last spring. The successful industry day drew about 30 companies interested in SSPD's extensive technology catalog. Future industry days are slated to be held every six to eight months. ❖

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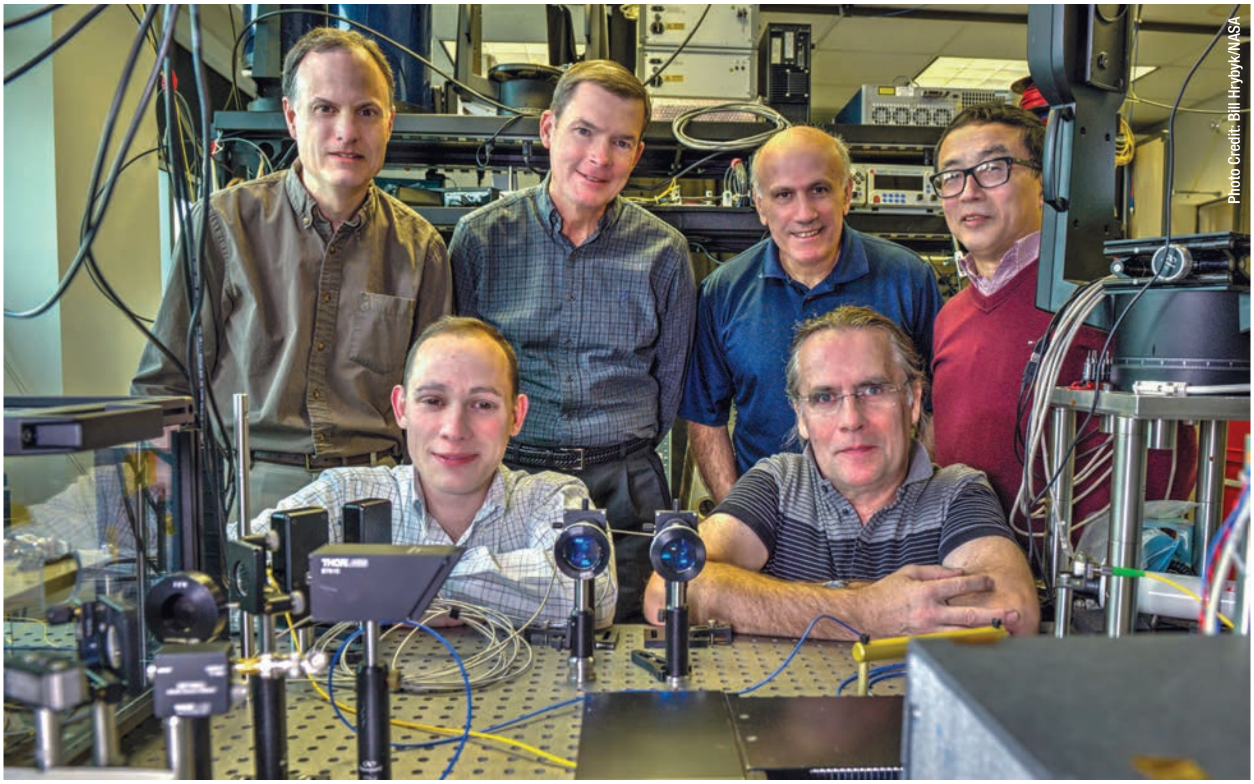
How Does the Wind Blow?

Team Leverages Proven Technologies to Build NASA's First Planetary Wind Lidar



Some of the components of the MARLI instrument are shown here with the team developing the instrument. Front row (left to right): Daniel Cremons and Graham Allan; (back row, left to right): Mike Smith, Jim Abshire, Haris Riris, and Xiaoli Sun.

Scientists have found a way to adapt a handful of recently developed technologies to build a new instrument that could give them what they have yet to obtain: never-before-revealed details about the winds on Mars and ultimately Titan, Saturn's largest moon.

"We pride ourselves in leveraging new technology," said Mike Smith, a planetary scientist who is collaborating with remote-sensing scientist Jim Abshire to create an experimental or demonstration test model of MARLI, short for the MARs LIdar for global climate measurements from orbit. "Why start from scratch when you can adapt recent technologies?"

NASA's First Planetary Lidar

The experimental MARLI, which the team believes will be mature enough to propose for a future orbiter mission in a couple years, could become NASA's first planetary wind lidar. Its chief job would be to profile the vertical distribution of atmospheric aerosols, including dust and ice particles, and directly measure wind velocities to determine how these conditions change over time, location, and season.

This information is vital to understanding everything from the transport of potential biomarkers, such as methane, to providing input for global circulation models that, among other things, help determine safe and precise landing locations for spacecraft.

Although the team conceived MARLI as a potential next-generation instrument for probing Mars' thin atmosphere, a modified version could be used to investigate Titan, Abshire said, adding that the team plans to use recently awarded NASA research-and-development funding to make the necessary adjustments and further advance the instrument.

"After 20-plus years of launching orbiters and rovers, we've learned a lot about environmental conditions on Mars, including temperatures and atmospheric gases," Smith continued. He added, however, that scientists have obtained very few direct measurements of the winds, which Mars rovers have clocked at 45 miles per hour or faster. And though Mars has a low-density atmosphere, the winds are often strong enough to completely

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enshroud the planet in dust. "If we were going to write a list of the things we don't know, winds would top the list."

If scientists know little about Martian winds, they know even less about atmospheric aerosols and dynamics on Titan, which is the only moon to host a dense atmosphere and the only object — aside from Earth — to have stable bodies of liquid on the surface, Abshire added.

The Solution

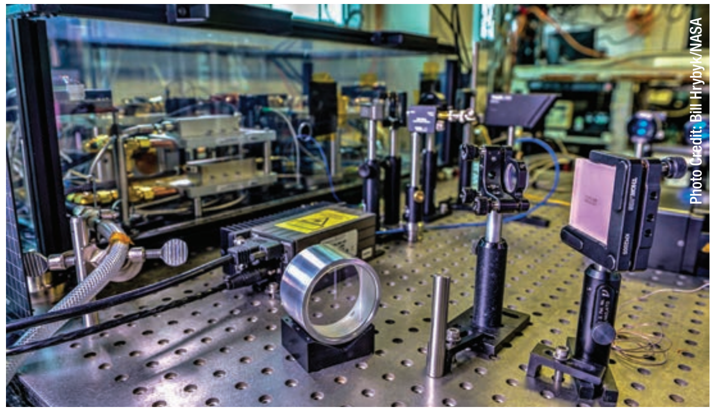
MARLI could provide a solution, its developers believe. From its orbit around Mars or Titan, its beam would be pointed roughly 30 degrees off nadir or in a direction pointing directly below a particular location. In that orientation, the instrument would operate much like Doppler radar. However, instead of radio waves, MARLI, with its onboard laser, would continuously pulse infrared light toward the surface.

Due to the presence of dust and ice particles in the atmosphere, the light would scatter during its journey to the surface, ultimately bouncing back to MARLI's onboard telescope, which would gather the returning backscatter signals and direct them to the instrument's detectors. The resulting data not only would reveal how fast the winds are blowing, but also profile globally dust and ice in an atmospheric column. This would give scientists a three-dimensional view of the dust and wind structure and how it changes with time, location, and season.

"Our approach has a high likelihood of success. It leverages key laser and receiver technologies from previous space lidar missions and other developments," including some that have mapped the topographies of Mars, Mercury, and the Moon, Abshire said. "The hardest part is getting a ride to Mars," Smith added.

The Adaptation of Technologies and Measurement Approaches

For example, MARLI's laser, to be built by the Herndon, Virginia-based Fibertek, Inc., is an adaptation of the device the company developed for the Goddard-developed Cloud Aerosol Transport System, or CATS. Though originally conceived as an aircraft-based instrument, CATS developers modified the instrument and launched it to the International Space Station in 2015 where it gathered more accurate global profiles of clouds and atmospheric aerosols. After 33 months in orbit, the instrument ended operations in late 2017.



The MARLI instrument breadboard is encased inside the clear case in the background. The cylindrical object in the foreground with the silver-colored outer shell is the optical etalon used in the lidar receiver.

MARLI's telescope, furthermore, is an adaptation of the one used on the Mars Orbiter Laser Altimeter, an instrument that flew on the Mars Global Surveyor, and its wind-measurement technique is similar to the one demonstrated by an airborne instrument called the Tropospheric Wind Lidar Technology Experiment, also known as TWiLiTE.

And its detector technology, created by team member Xiaoli Sun and his industry partner, the Dallas, Texas-based DRS Technologies, represents a new technology adapted for wind measurements. The detector is the world's first photon-counting detector sensitive to the mid-infrared wavelength band — a spectral sweet spot for several remote-sensing applications, including the detection of ice (CuttingEdge, Summer 2015, Page 6).

Coupled with a device that converts Doppler-shifted backscatter signals into actual photon numbers, the detector is unique. Each sesame seed-sized detector registers each converted photon in the returning signal, giving it unprecedented sensitivity. In addition to being baselined for MARLI, the detector technology has found homes in two airborne laser instruments that Abshire and Haris Riris, another MARLI team member, designed to measure carbon dioxide and methane in Earth's atmosphere.

Because of this leverage, "MARLI is uniquely capable of answering these important science questions with a single instrument," Abshire said. "This will allow us to better understand the things that are happening in the atmosphere, including the transport of dust and ice particles — the genesis of dust storms. Right now, these basic questions still remain." ❖

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Sciencecraft: The Future of NASA?

NASA needs to seriously consider a course correction in the way it builds certain types of space observatories, particularly those that are smaller, higher risk, experimental, and created by modestly sized teams with limited budgets, said Goddard Senior Business Development Manager and forward thinker Bill Cutlip.

Toward that end, he has studied a new type of space-based observatory called sciencecraft.

Under this concept, mission developers would build and integrate the spacecraft bus and the instrument as a homogeneous observatory instead of button-holing an instrument onto a particular spacecraft bus — a complete reversal in the way that NASA currently approaches the development of both traditional and SmallSat missions where few, if any, subsystems are shared.

Bill Cutlip believes NASA needs to seriously reconsider a course correction in the way that it builds small spacecraft. With his FY17 R&D funding, he investigated a concept called sciencecraft.

"The sciencecraft concept offers the cost benefit of achieving ambitious mission science goals while using these smaller, fully integrated observatories," Cutlip said, referring to the concept that he advanced with Goddard's Internal Research and Development program funding. "This is the future."

Mini-LHR Used as a Test Case

To demonstrate the concept's feasibility, Cutlip teamed with Goddard Earth scientist Emily Wilson to establish a test case with a version of her patented mini Laser Heterodyne Radiometer, or mini-LHR. The suitcase-sized instrument is used in field campaigns to measure the emissions of greenhouse gases from Alaska's permafrost. Wilson also is working with the Lawrence Livermore National Laboratory to adapt the highly portable instrument for use on a 6U CubeSat mission (*CuttingEdge*, Winter 2015, Page 7). It is this version that served as the heart of the sciencecraft effort.

The two technologists specifically evaluated which spacecraft and instrument subsystems could be shared or paired with one another, thereby simplifying and potentially lowering the cost and size of these missions, while reducing the amount of time it takes to build and integrate them. "What we asked during this exercise, for example, is 'do I need a separate power supply for the spacecraft and instrument?' The answer is probably not," Culpit said.

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Another possibility for better integrating the instrument and its spacecraft is integrating 3-D printing in the design and fabrication of all aspects of the sciencecraft, Cutlip said.

This approach would require engineers to adopt a "free-space approach" to packaging; in other words, the placement of subsystem mounting points, for example, would be freed from where they historically are positioned. The same could be said for structure and harnesses, Cutlip said. Preliminary work under his IRAD demonstrated that wiring could be 3-D printed into flexible structures that can bend around corners.

Far from an impossibility, Goddard technologist Mahmooda Sultana is teaming with Boston's Northeastern University to print a multifunctional sensor platform with the university's Nanoscale Offset Printing System (CuttingEdge, Fall 2017, Page 2). The goal is to use 3-D printing to fabricate a suite of sensors on the same platform, substantially simplifying the assembly of sensors that typically require time-consuming handwork to wire together components. With 3-D printing, these components would be laid down in one process.

Another technologist, Beth Paquette, currently is investigating the use of direct-write printing techniques to build 3-D detector assemblies that were not previously possible with traditional assembly processes. Instead of melting and fusing materials in precise locations, as in the case of many 3-D printers, aerosol jet printing or direct write uses a carrier gas and printer heads to deposit a fine aerosol of metal particles, onto a surface. This technology prints around bends, on spheres or on something flat, and on a flexible surface (CuttingEdge, Spring 2016, Page 11).

"What they want to do is the same thing I want to do," Cutlip said.

If the sciencecraft concept grows legs, Cutlip believes it would be ideal for rapid prototyping and small, inexpensive, and higher-risk missions that fall under NASA's Class-D mission category.

"Class-D is the right place to do this," Cutlip said. "Sciencecraft offers a more efficient way to take advantage of the growing assortment of access-to-space options or to create on-the-fly probes for use during human-based exploration missions in deep space. Mass- and volume-efficient sciencecraft could potentially be flown on the next smaller launch vehicle, which will ultimately increase the science return per dollar," Cutlip said. ❖

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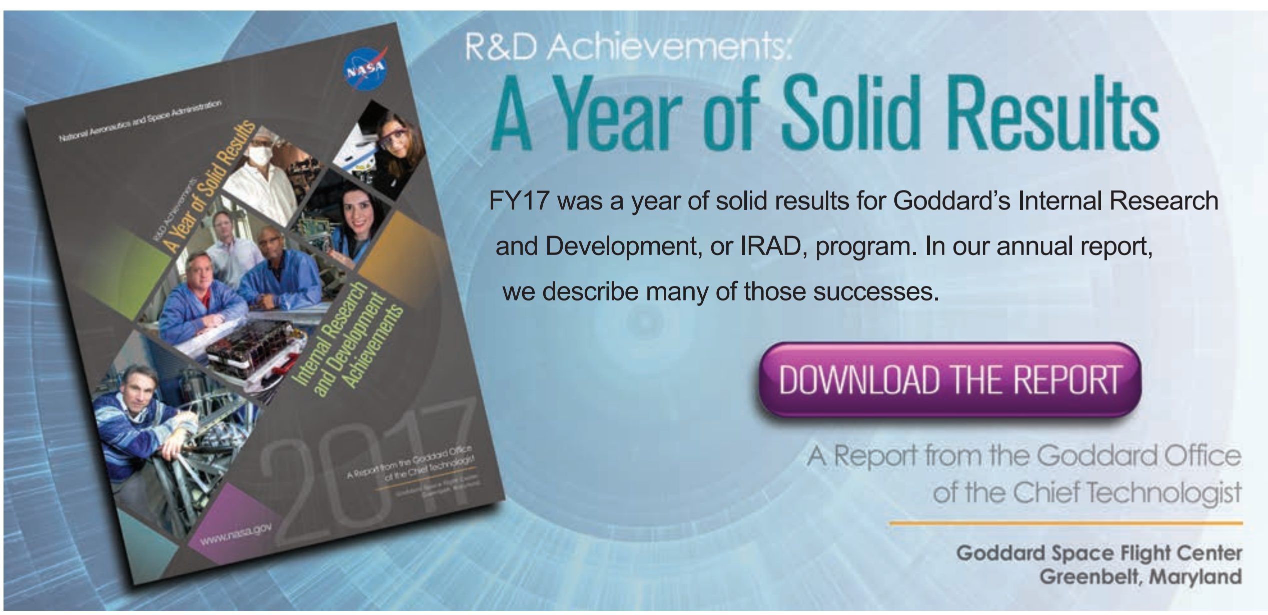

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